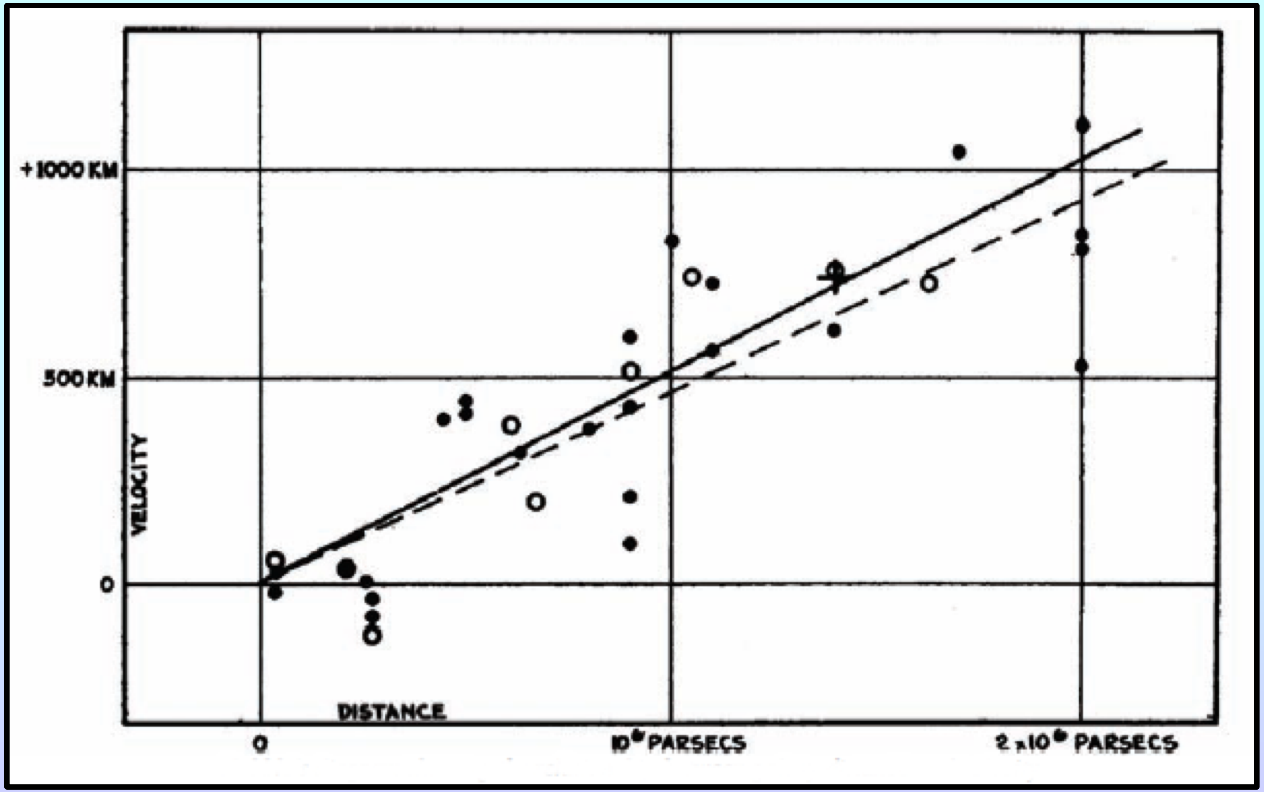
# A Bit of History

- 1917: William de Sitter uses general relativity to describe an expanding universe
- 1917: Einstein, preferring a static, unchanging universe, adds a constant of integration, the "Cosmological Constant"
- 1929: Hubble discovers that the universe is expanding!!




Hubble's original redshift-distance diagram

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- 1927: George Lemaître makes the first estimate of the "Hubble Constant,'' and proposes the Big Bang model of the universe. (Note: the term "Big Bang" wasn't coined until much later, when Fred Hoyle was trying to discredit it.)
- 1948: George Gamow predicts the existence of background radiation from the Big Bang using nucleosynthesis arguments

# Gamow's Argument

- In its first second, the universe must have been a hot, dense mixture of electrons, protons, neutrons, neutrinos, and photons
- At an age of ~ 1 sec, the ratio of protons to neutrons must have been unity as interactions with neutrinos mediate the conversion of neutron to protons, and vice versa
- At an age of ~2 sec, the universe would have expanded enough to allow neutrinos to escape. This would have cause the ratio of protons to neutrons to increase.
- Later, when the universe cooled enough for fusion to occur, the proton-neutron ratio would have been ~7. Nucleosynthesis (the proton-proton chain) would have made the mass fraction of helium ~ 0.25. This is what is observed.
- Thus the universe must have been very hot at one point, leading to a background radiation.

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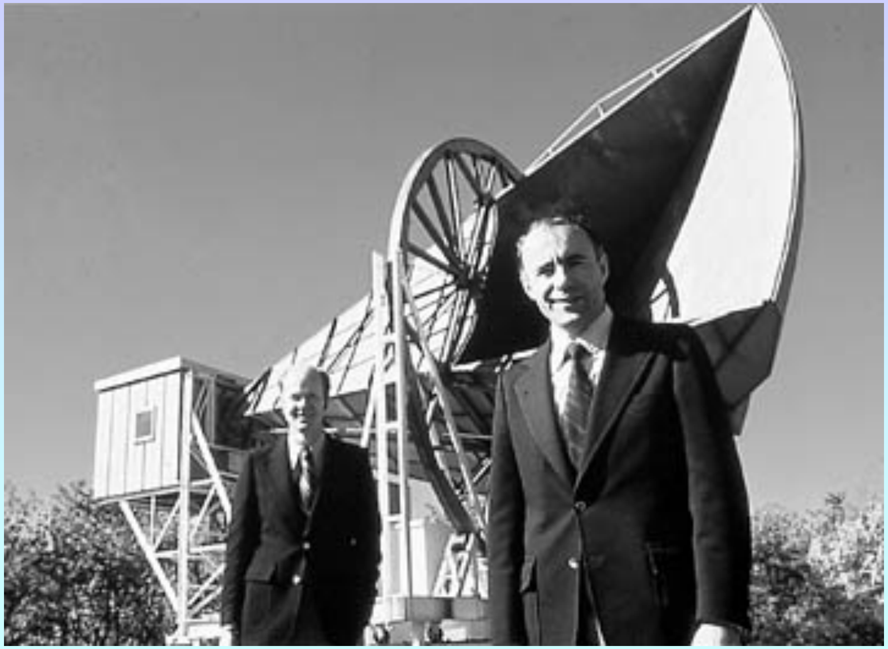
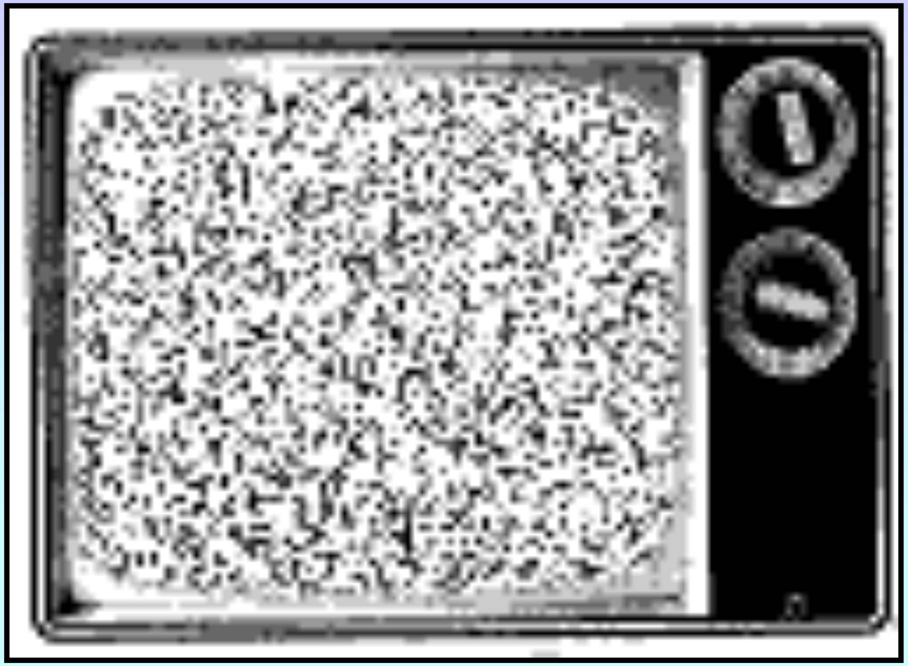
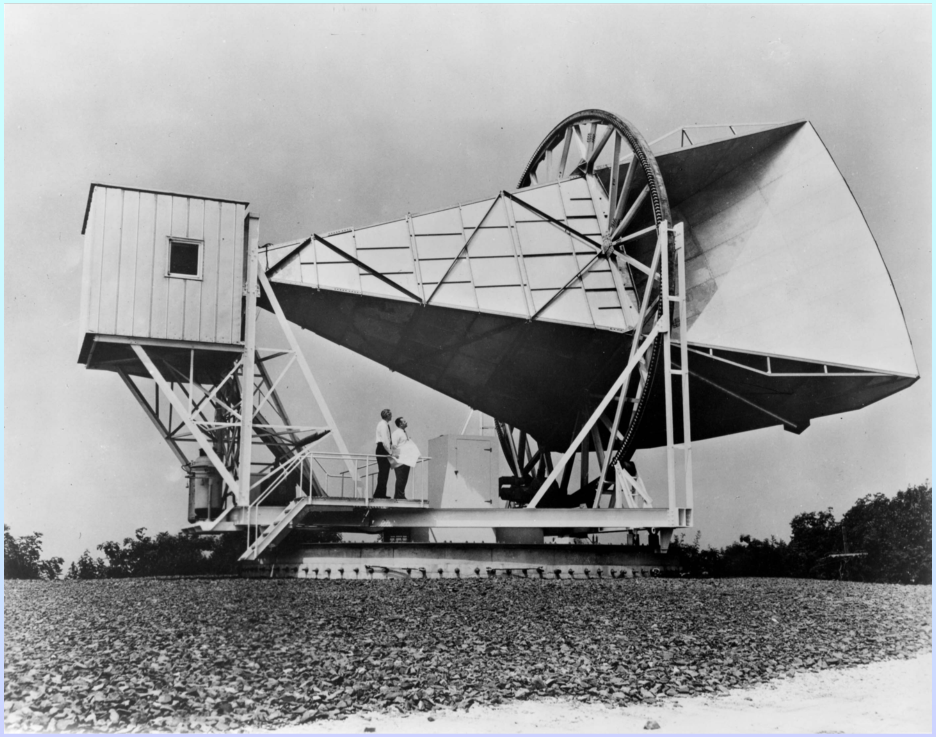
- 1948: George Gamow predicts the existence of background radiation from the Big Bang using nucleosynthesis arguments
- 1965: Arno Penzias and Robert Wilson discover the noise in a radio antennae won't go away. It is the 2.73 K cosmic microwave background radiation (CMB).



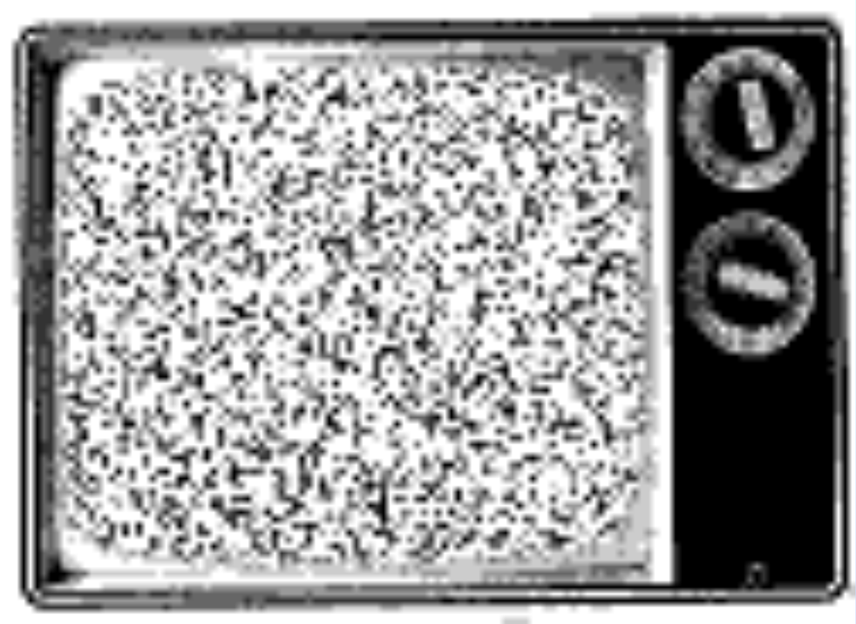


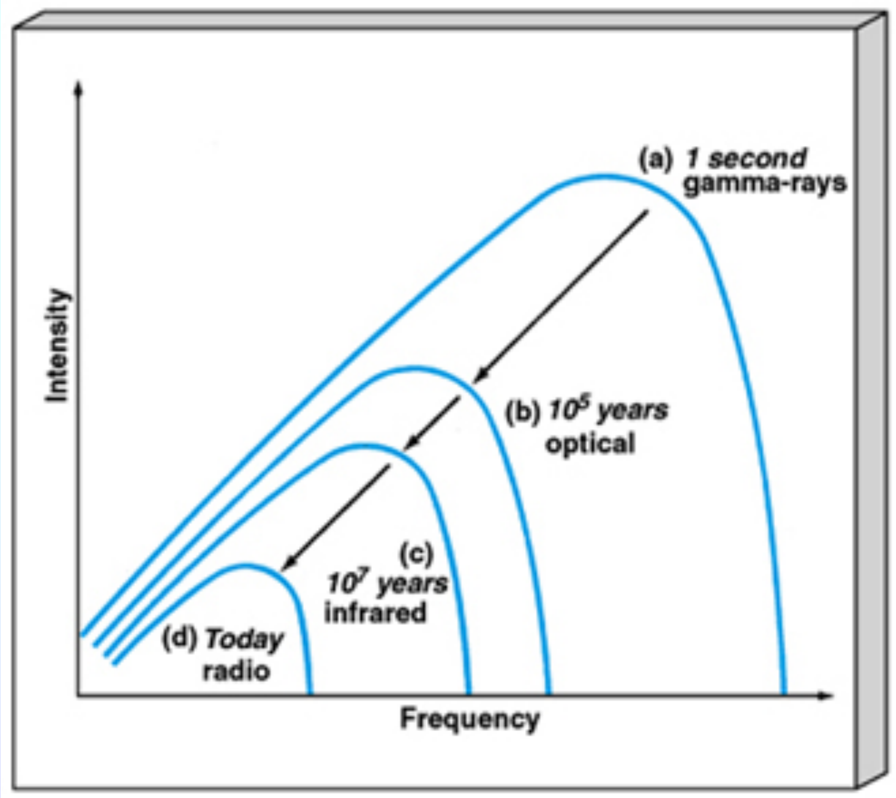


Penzias and Wilson and their microwave antenna

# The Cosmic Microwave Background

If the universe is expanding, then at one time, it must have been very dense, and (through the equation of state) very hot. It therefore emitted blackbody radiation. When the universe is ionized, photons interacted with matter, and their mean-free path was short; once recombination occurred, interactions ceased and the universe became transparent. These photons are still with us today, though they have been redshifted.

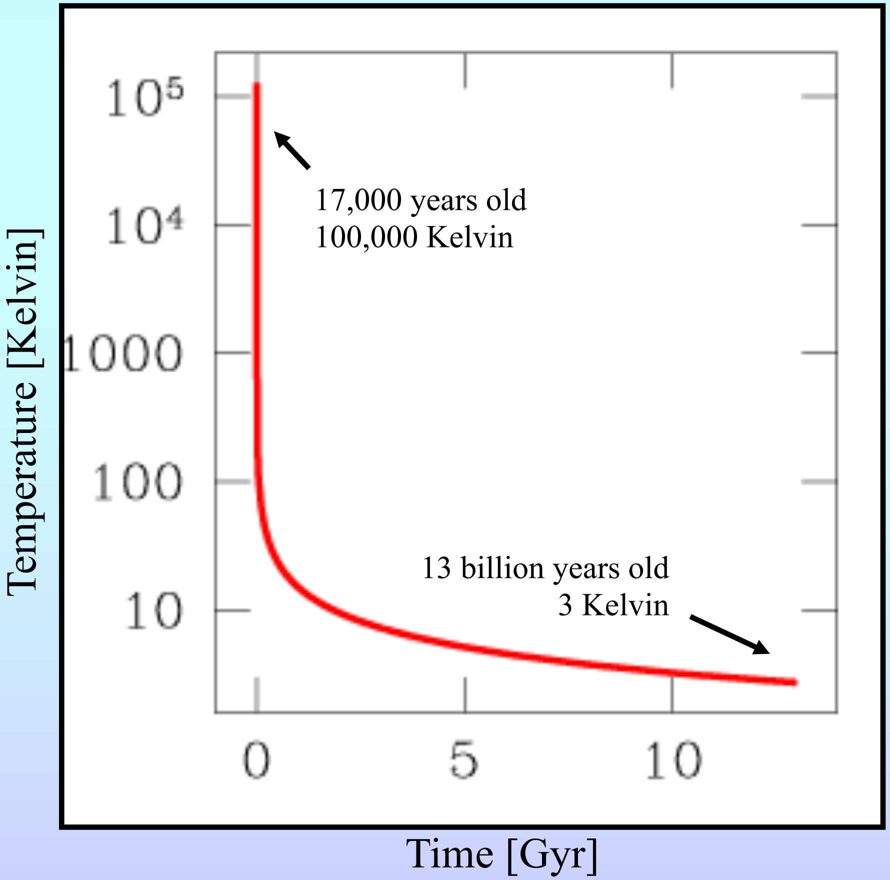




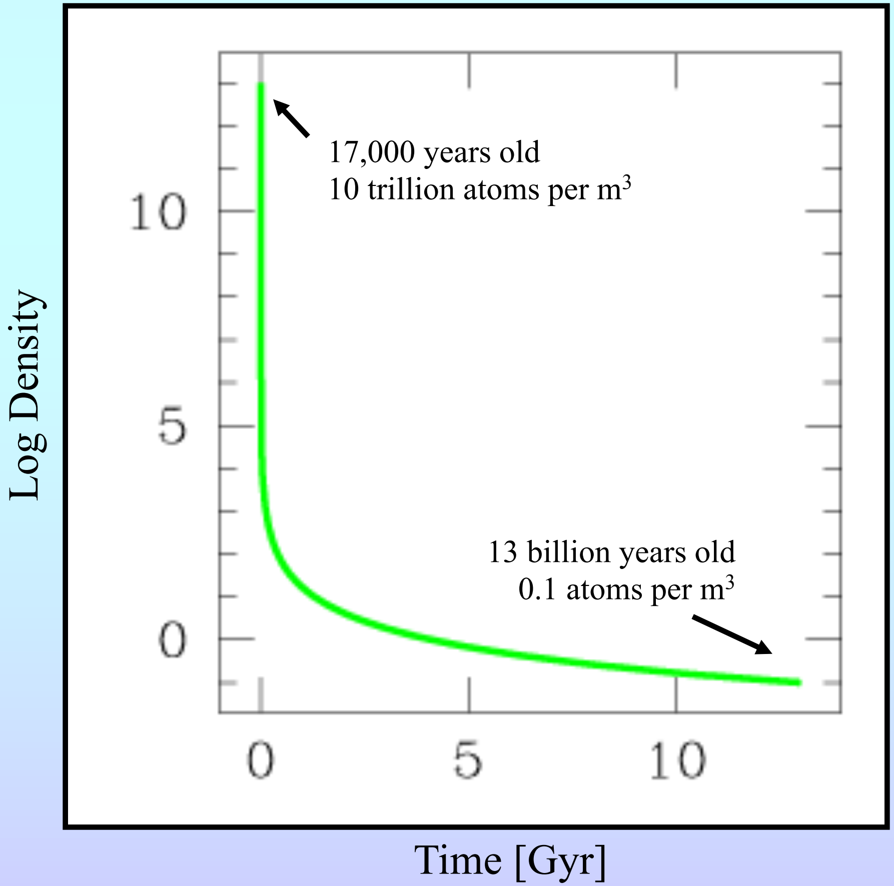
# Temperature Evolution of the Microwave Background

The expansion of the universe has caused the matter density of the universe to drop by $(1+z)^3$, the photon energy to decline as $(1+z)$, and the microwave background temperature to decline as $(1+z)$.

**Temperature versus Time**




**Density versus Time**



# The Cosmic Microwave Background

We can calculate the epoch of last scattering through the Saha equation. Recall that

$$\frac{N_{i+1}}{N_i} N_e = 2\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} \frac{u_{i+1}}{u_i} e^{-\chi/kT}$$

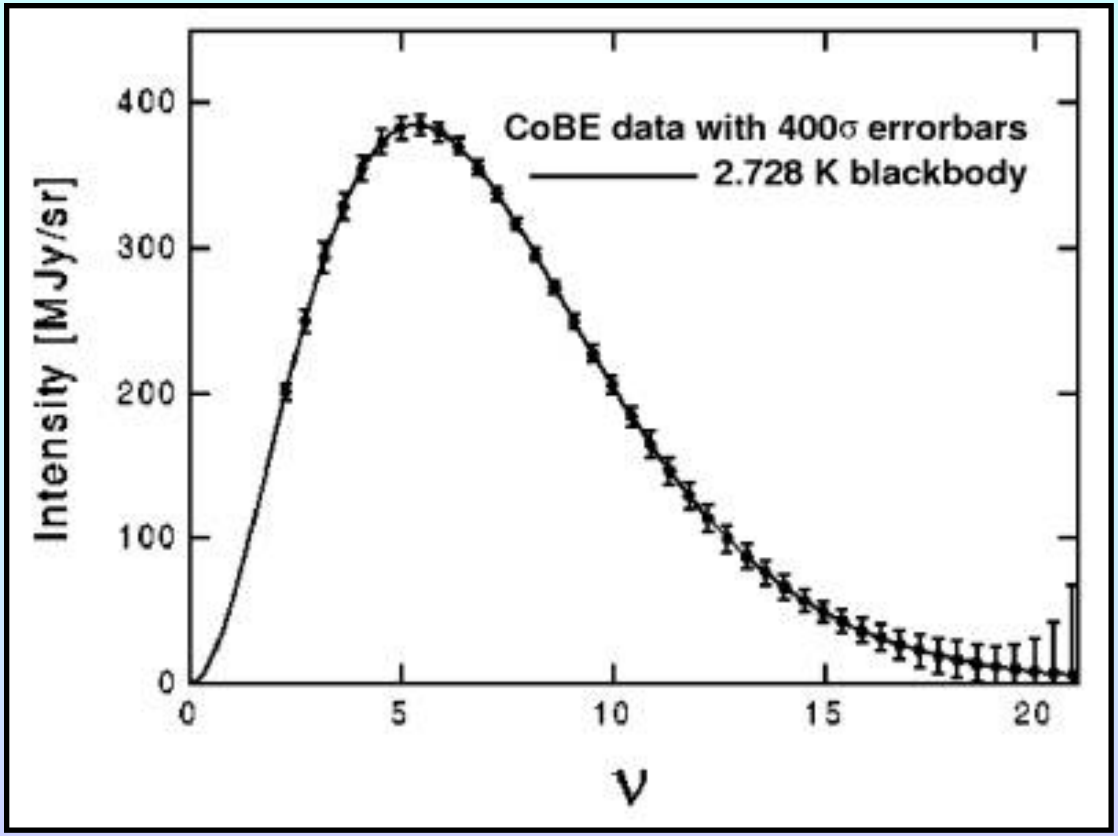
For pure hydrogen, $N_e = N_{i+1}$, $N = N_i + N_{i+1}$, $u_{i+1} = 1$, and $u_i = 2$. If we let $x = N_{i+1}/N$, and substitute $\rho = N\, m_H$, $T = T_0\,(1+z)$, and $\rho = \rho_0\,(1+z)^3$, then

$$\frac{x^2}{1-x} = \left(\frac{2\pi m_e kT_0}{h^2}\right)^{3/2} \frac{m_H}{\rho_0} (1+z)^{-3/2} e^{-\chi/kT_0(1+z)}$$

The universe became transparent when it went from being ionized to neutral, i.e., when $x \sim 0.5$. Through the equation, this corresponds to $z \sim 1500$, and a recombination temperature of $T \sim 4000$ K.

# The Cosmic Microwave Background

- 1948: 3 degree blackbody emission from the entire universe predicted by George Gamow
- 1965: 3 degree blackbody emission found by Arno Penzias and Robert Wilson
- 1998: Blackbody spectrum measured by the COBE satellite

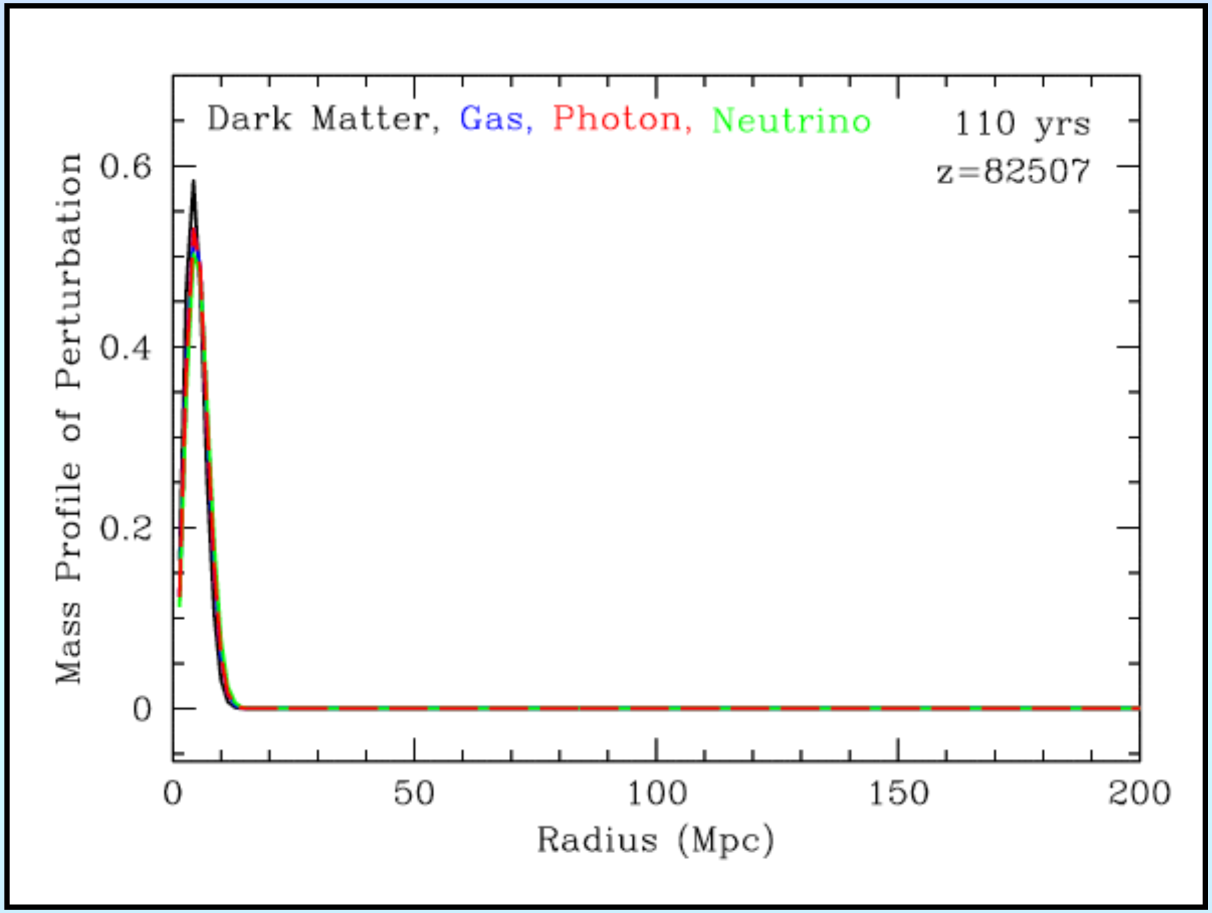



Note the size of the error bars!!!

# The Uniformity of the CMB

Consider a uniform universe with cold (slow-moving) dark matter, baryonic gas, photons, and hot (fast-moving) neutrinos. Now add in a small positive density perturbation that affects all species.

Since the gas is ionized, photons have very small mean-free paths, and are strongly coupled to the gas.



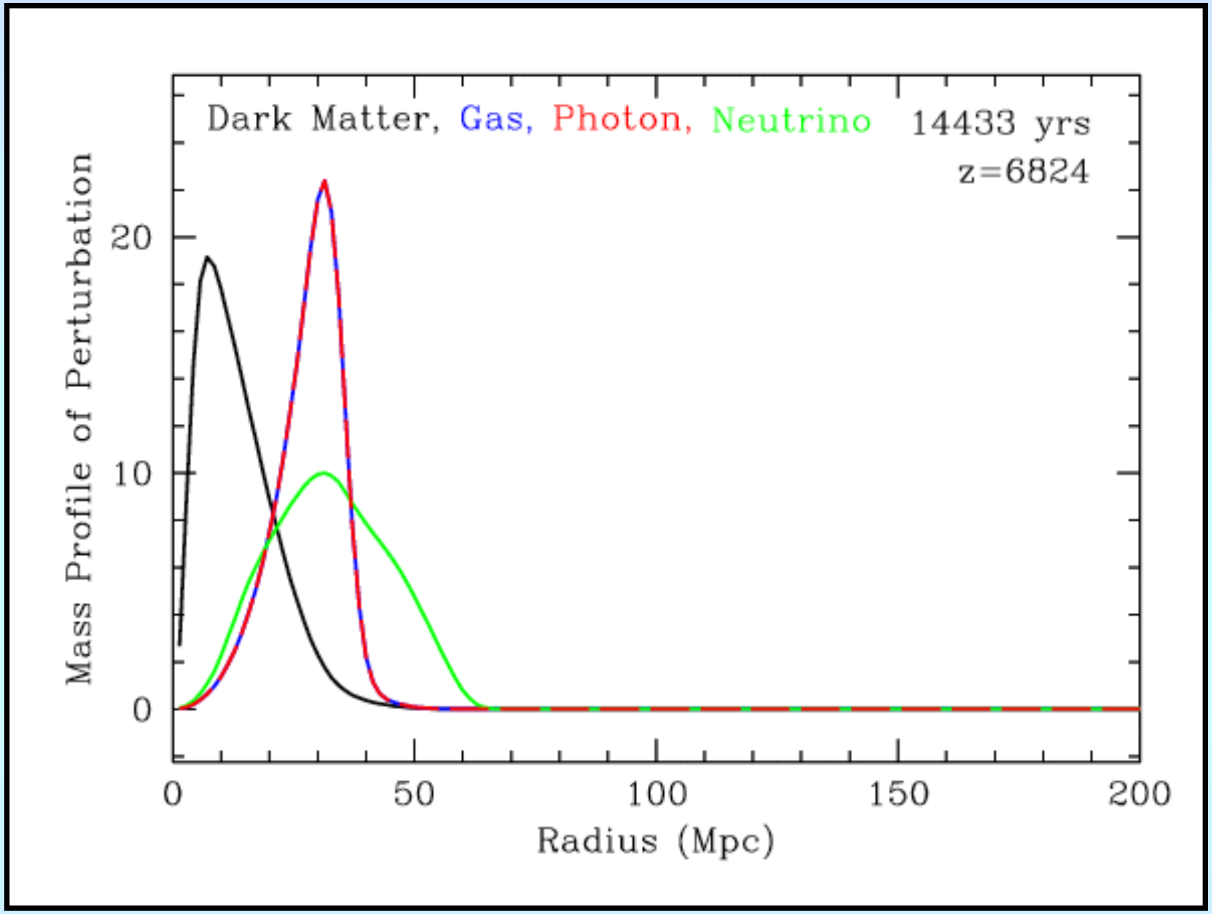

Initial Perturbation

# The Uniformity of the CMB

Since the dark matter is cold and (at very best) weakly interacting, it stays put, gravitationally attracting other (dark) matter.

Since neutrinos are hot and non-interacting, they stream out freely.

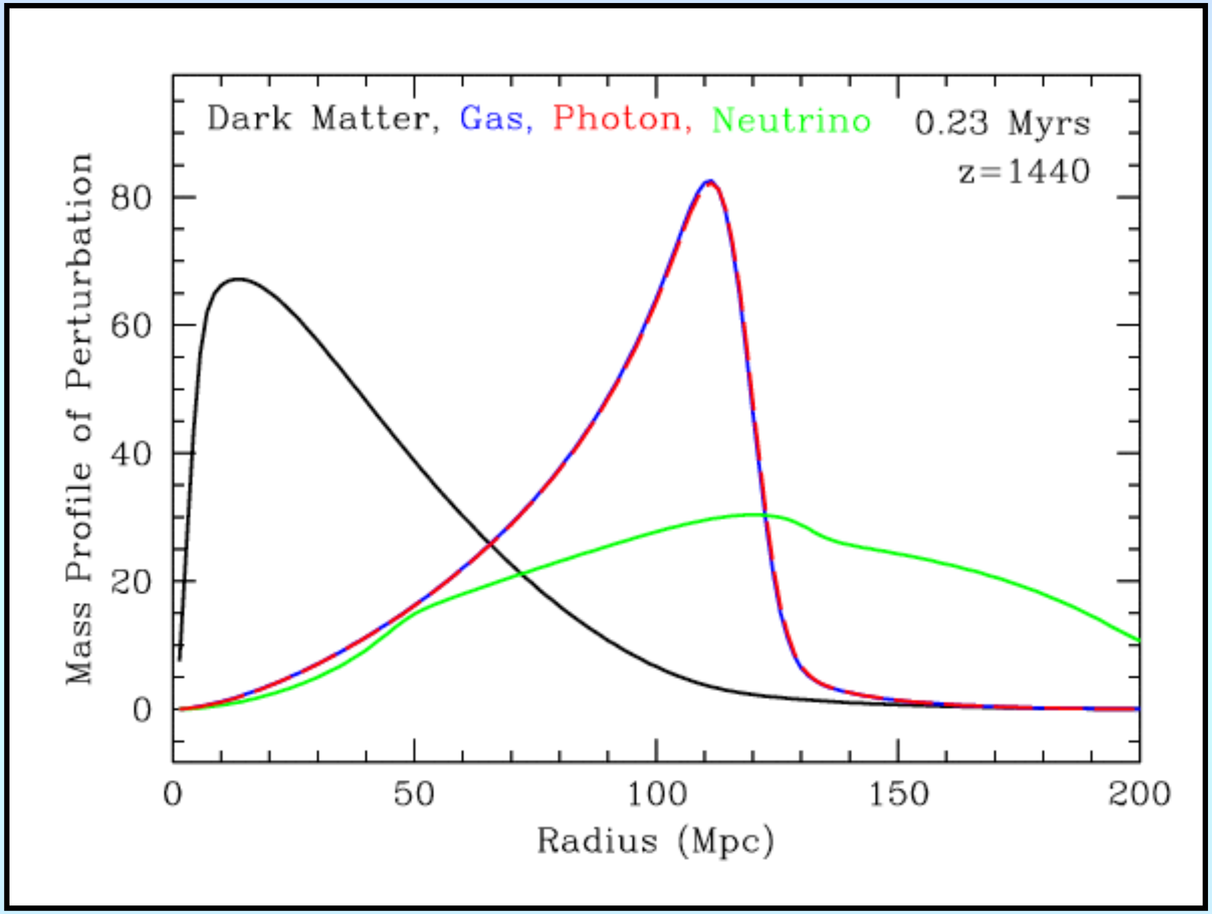
The over-density of gas and photons causes a pressure wave to propagate.




Acoustic Wave Begins to Propagate

# The Uniformity of the CMB

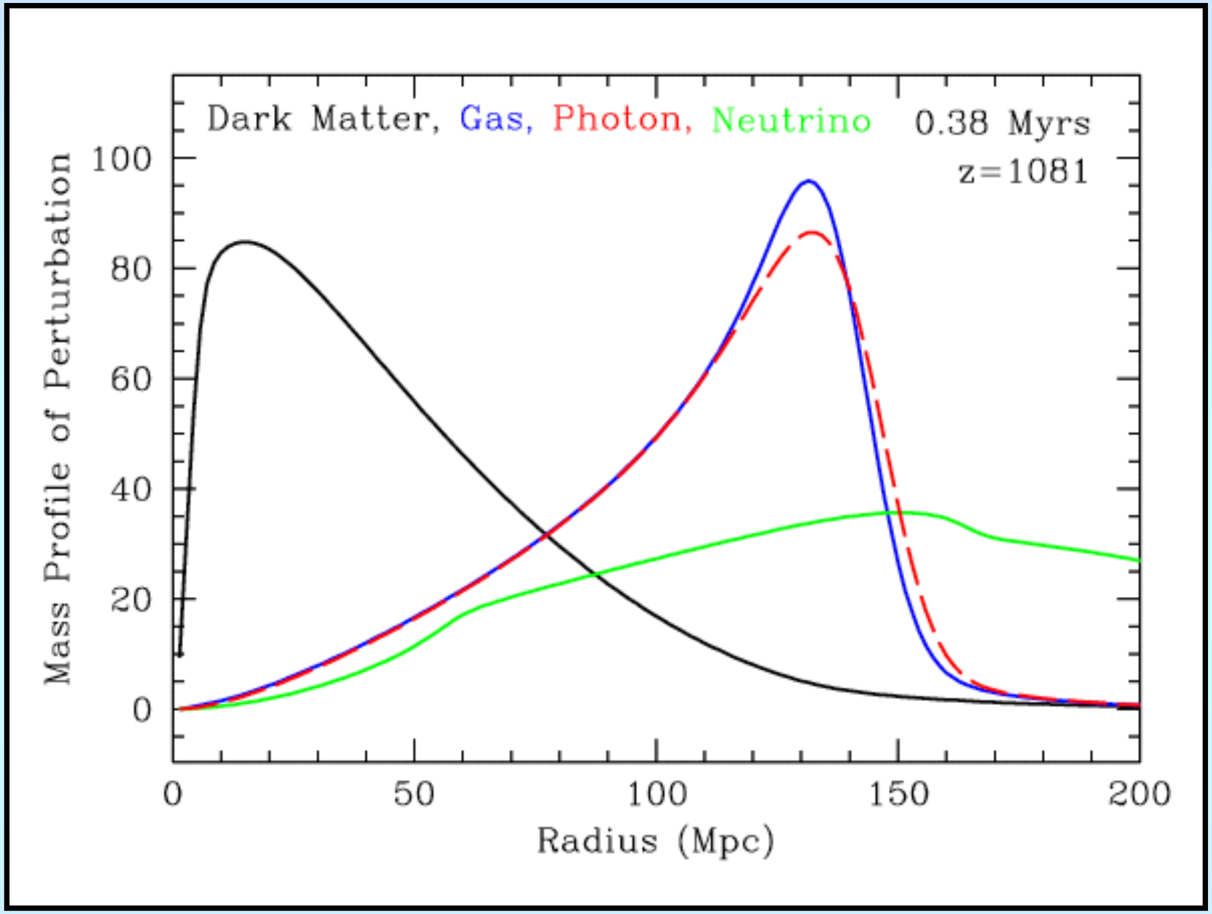
Photons and neutrinos leave the central perturbation, leaving a concentration of dark matter. The neutrinos continue to spread out, and the acoustic wave (driven largely by the energy of the photons) continues to propagate.




Matter infalling to the dark matter clump

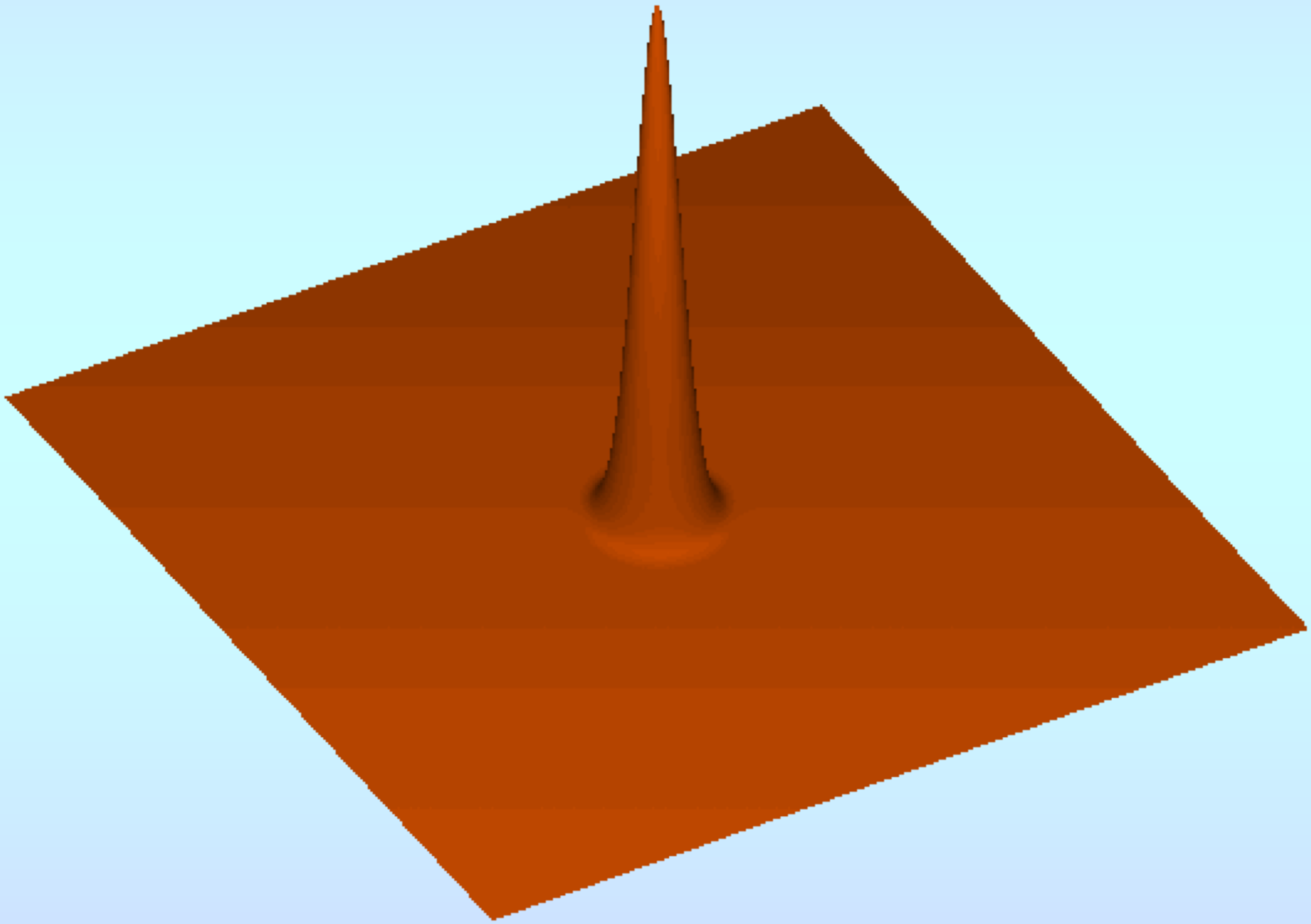
# The Uniformity of the CMB

The universe cools, so the gas begins to recombine. Photons begin to leak through the partially neutral gas, decreasing the speed of the pressure wave until it stalls. After recombination, photons are free to stream across the universe.



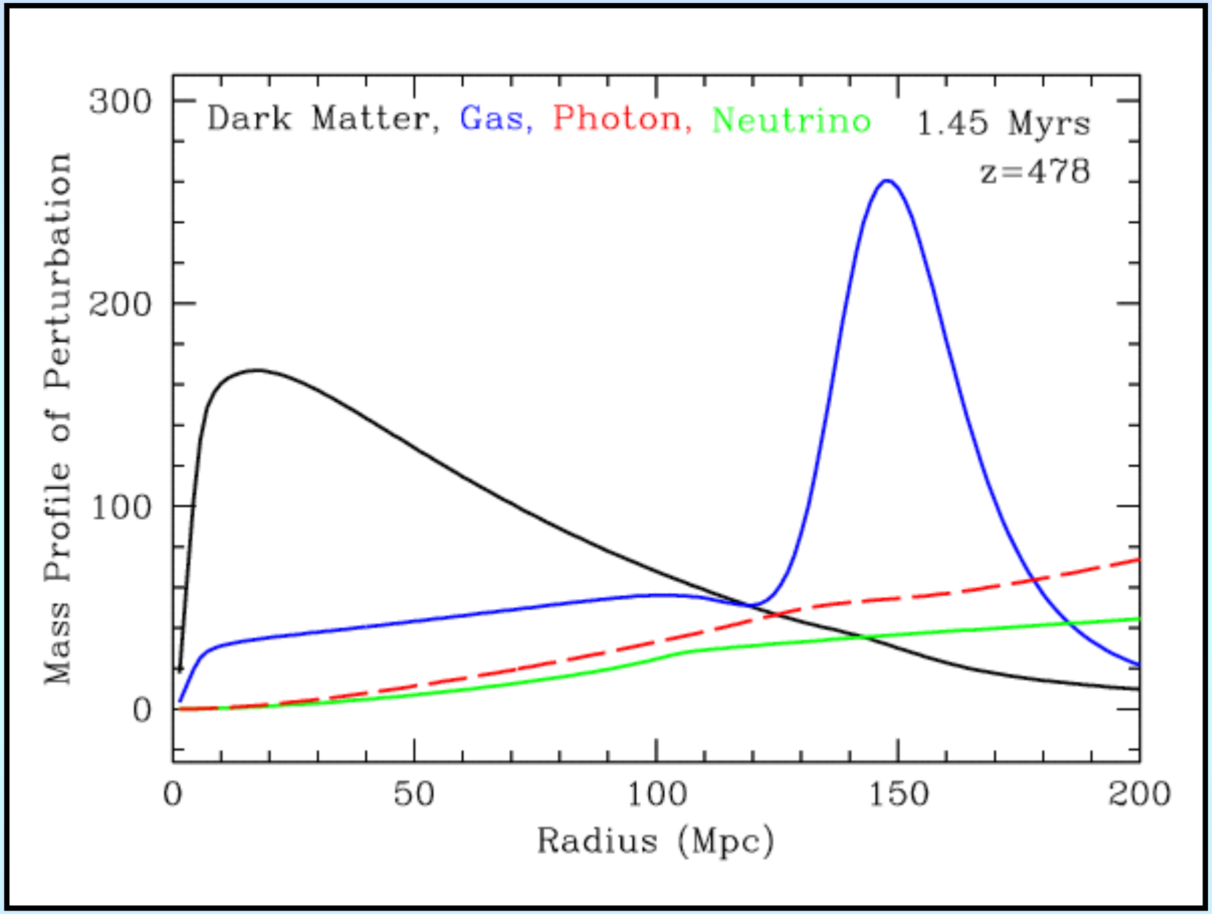

The beginning of decoupling.

# The Acoustic Wave



# The Uniformity of the CMB

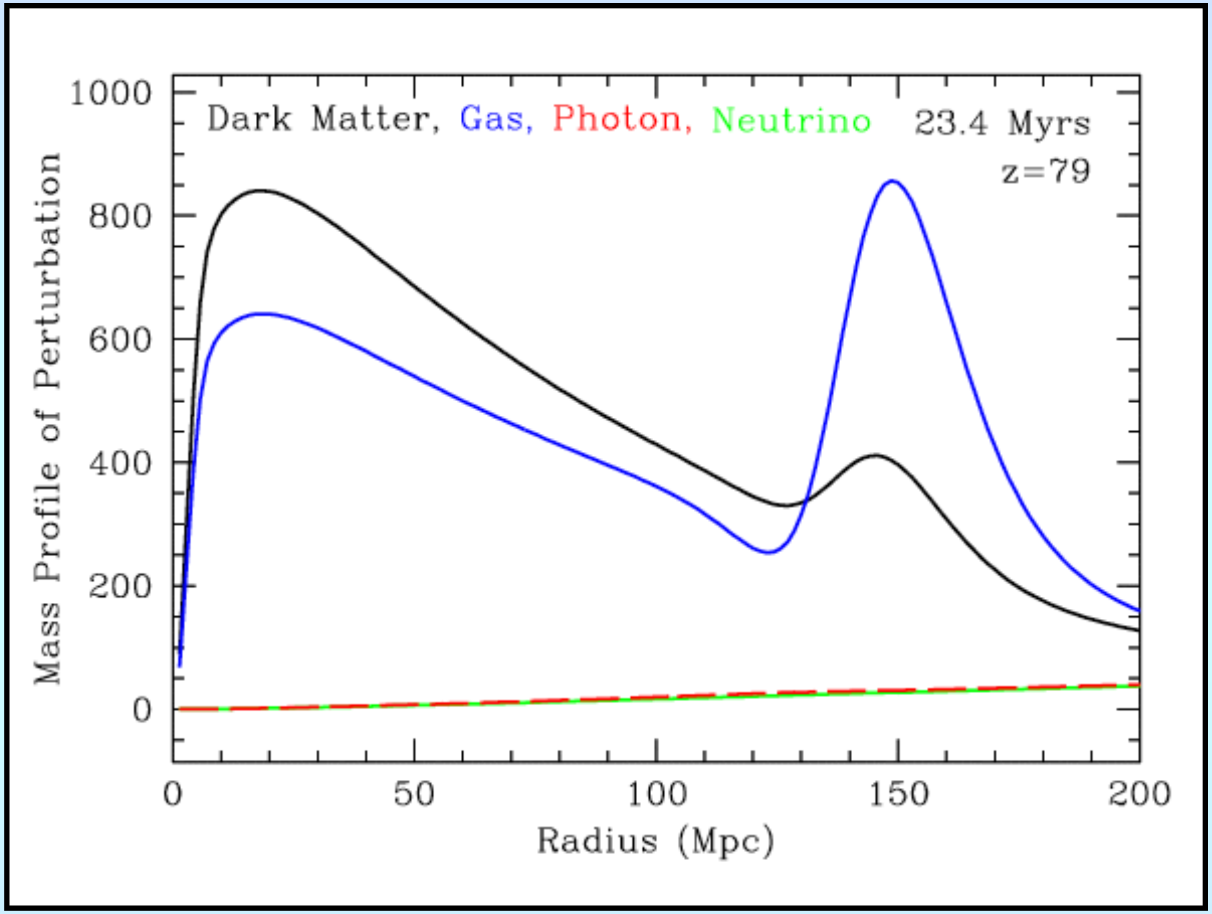
The dark matter and gas perturbations both begin to attract matter gravitationally. Both perturbations increase in strength and start to grow by many orders of magnitude.




Structure begins to grow

# The Uniformity of the CMB

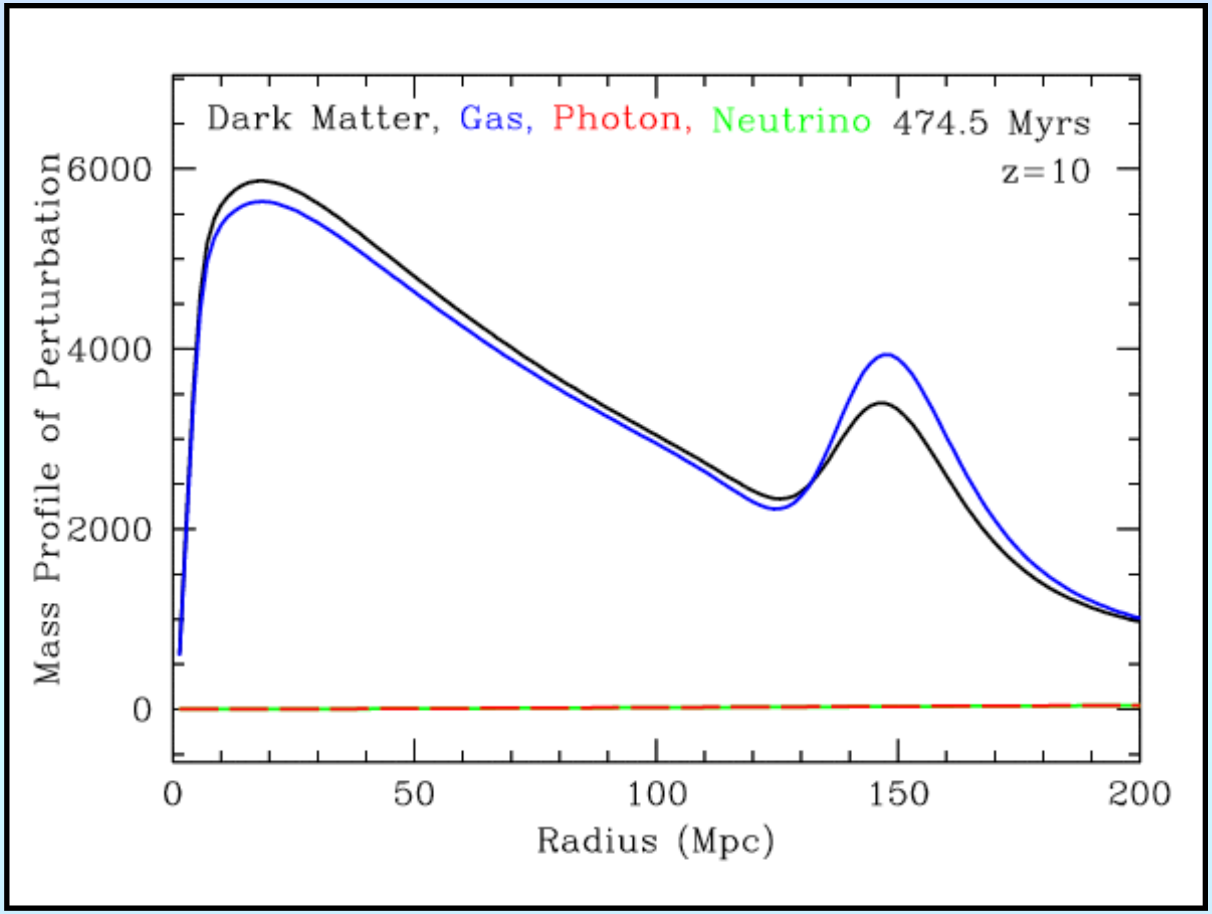
The photons and neutrinos are now distributed (almost) uniformly across the universe. The perturbations continue to grow in amplitude as matter falls into the potential wells. Thus, the distributions of gas and dark matter begin to look the same.




Dark matter begins accumulate in the acoustic peak, and gas falls into the dark matter peak.

# The Uniformity of the CMB

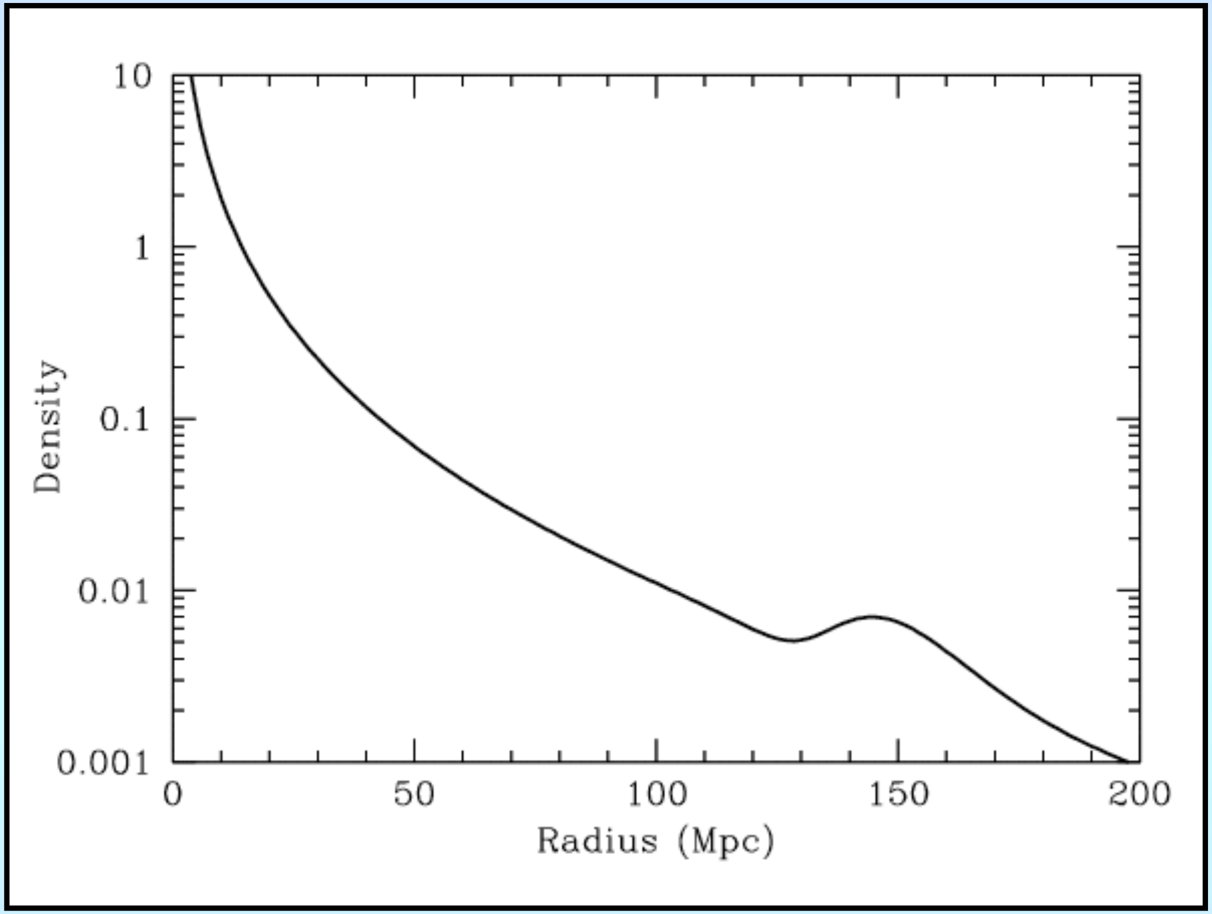
The acoustic peak's contrast begins to decline, as the gas is forced to follow the potential defined by the (five times more massive) dark matter component.




The potential wells defined by the dark matter begin to define the distribution of all matter.

# The Uniformity of the CMB

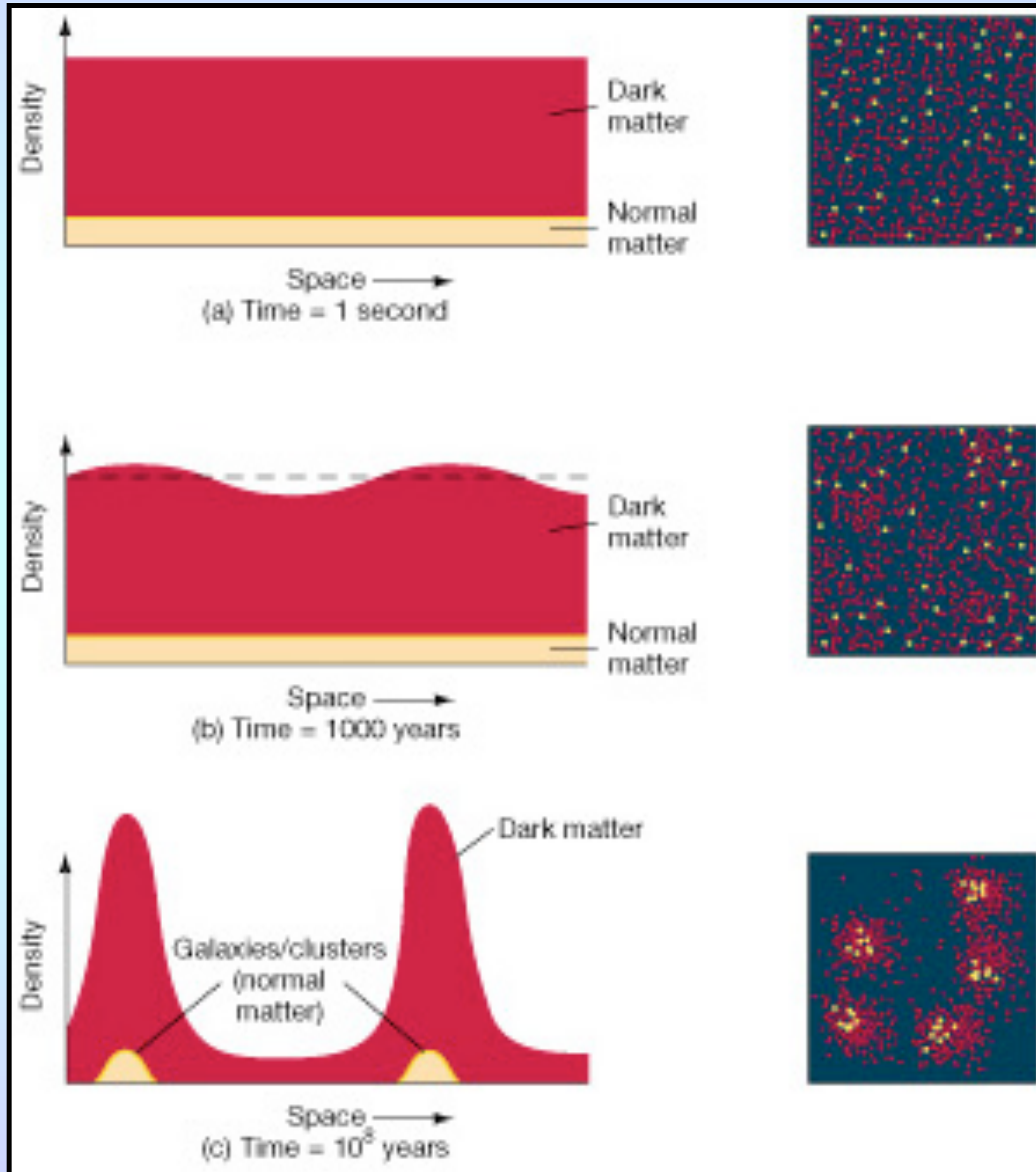
Galaxies now form in the regions of highest density. A ~ 1% enhancement in the galaxy density exists roughly 150 Mpc from the primary peak.




The distribution of galaxies at later times.

# The Dominance of Dark Matter

Note: most of the structure we see in today's universe comes simply from the gravitational attraction of collisionless dark matter. The baryons are largely just around for the ride.



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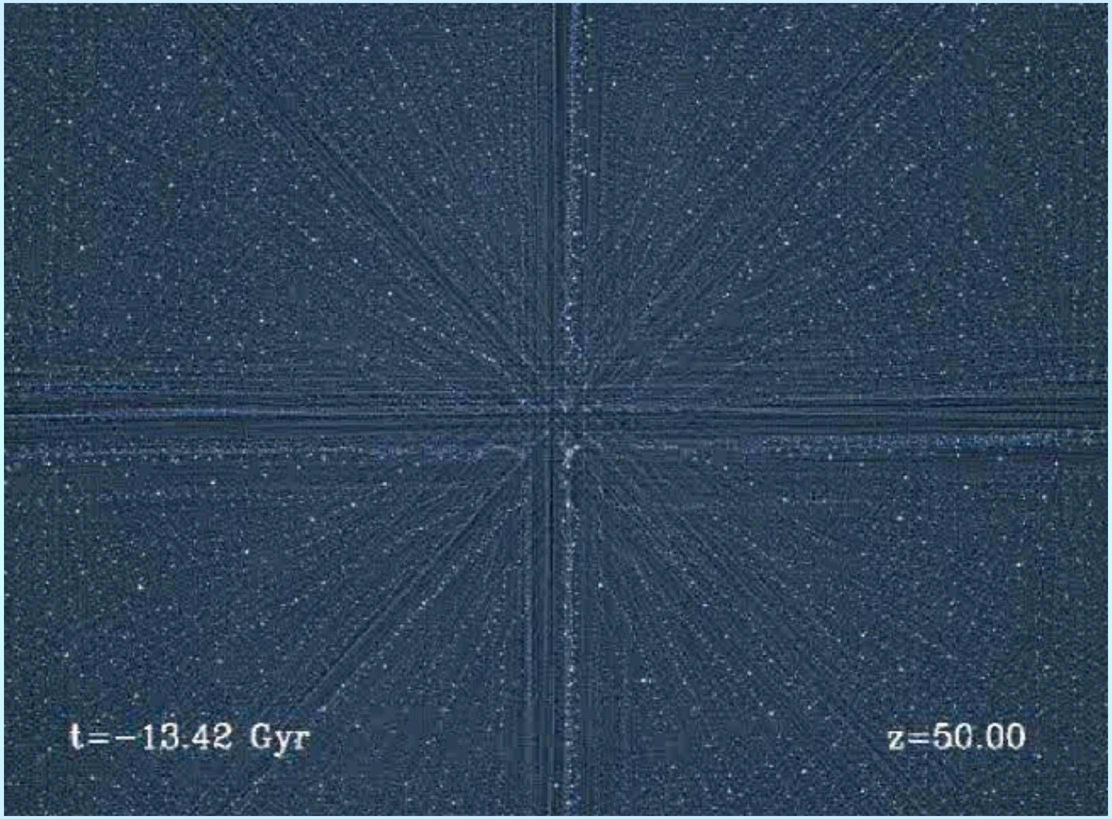
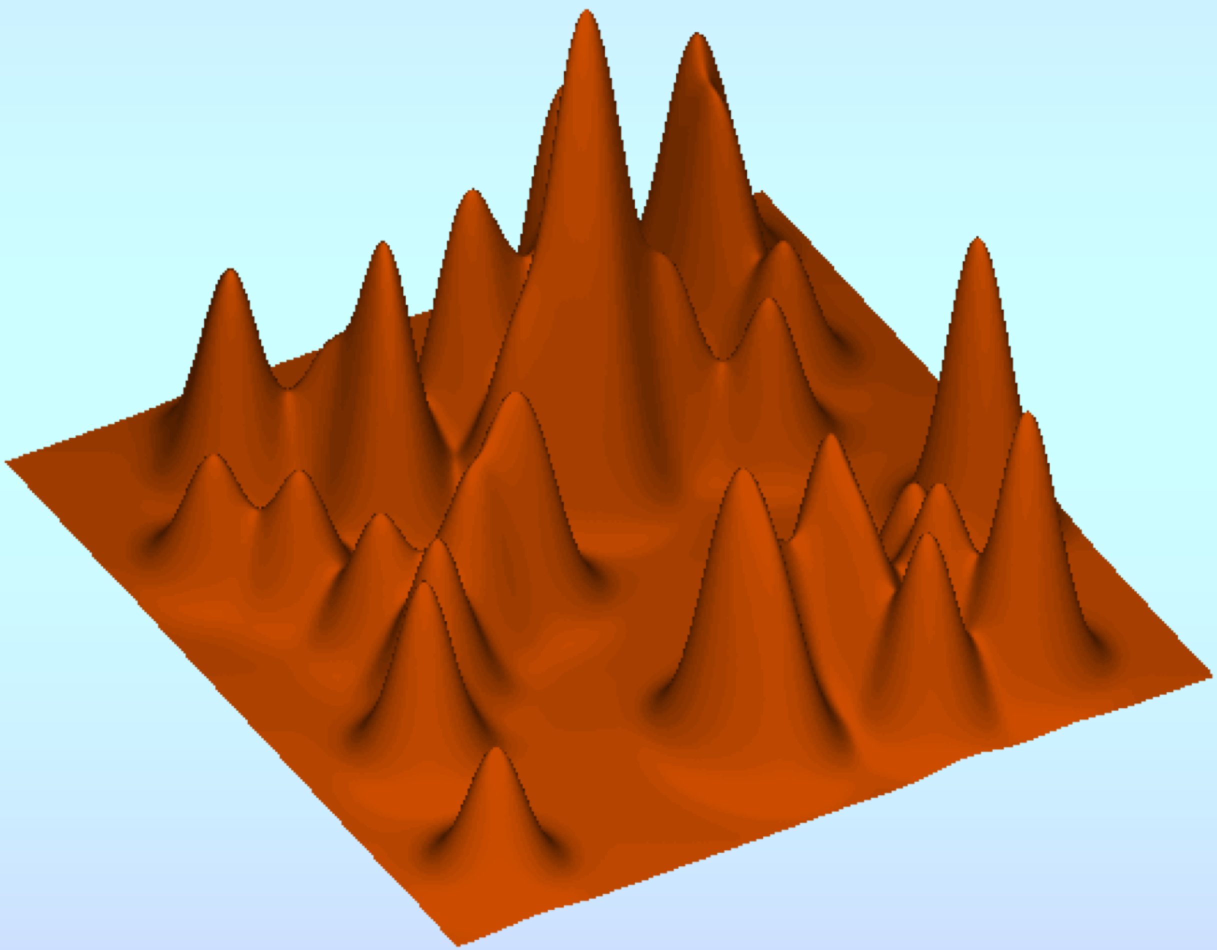


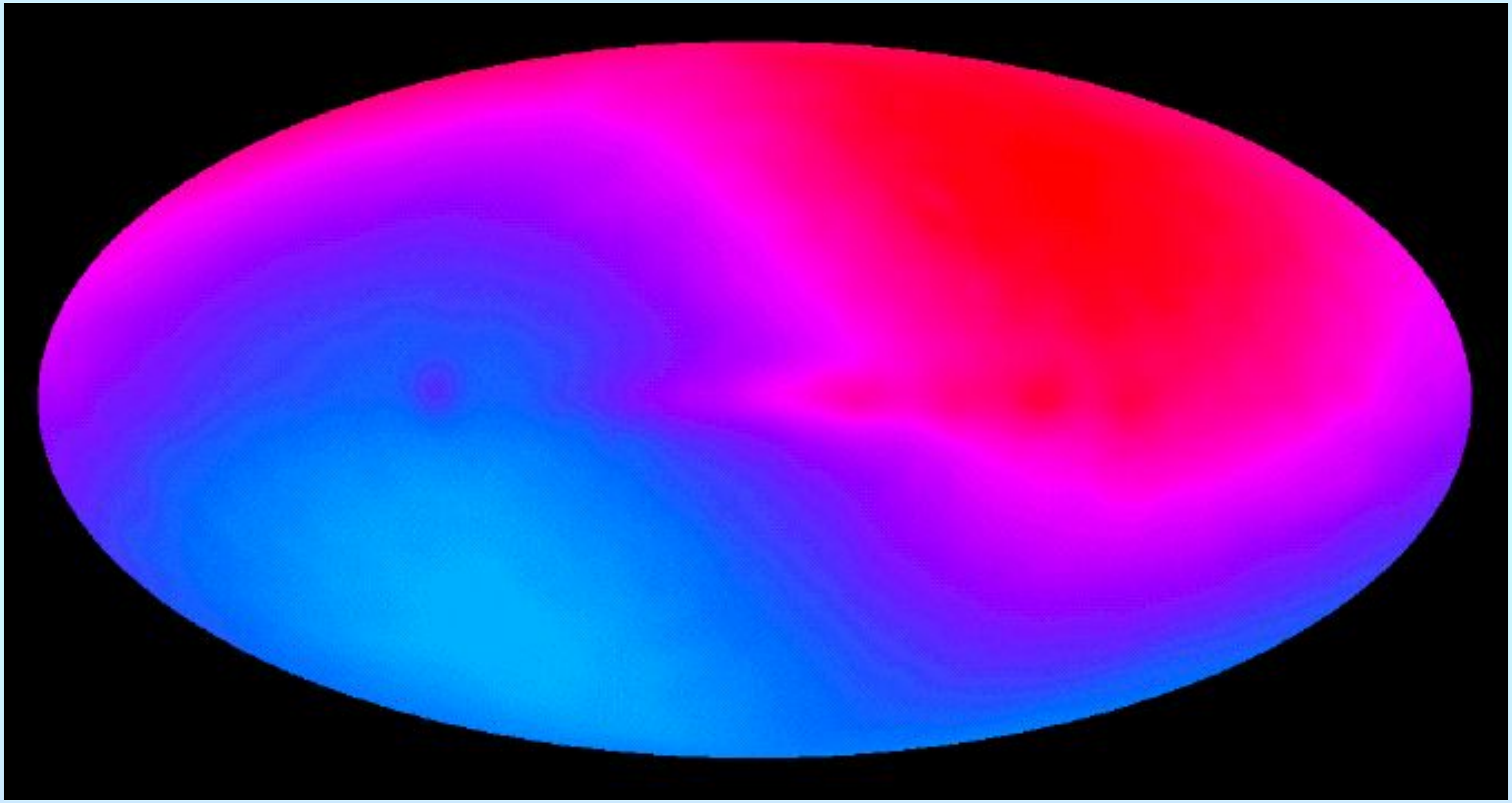
# The Microwave Background Fluctuations

All the individual fluctuations overlap, but the acoustic peak is still imprinted in the universe.



# The All-Sky Microwave Background

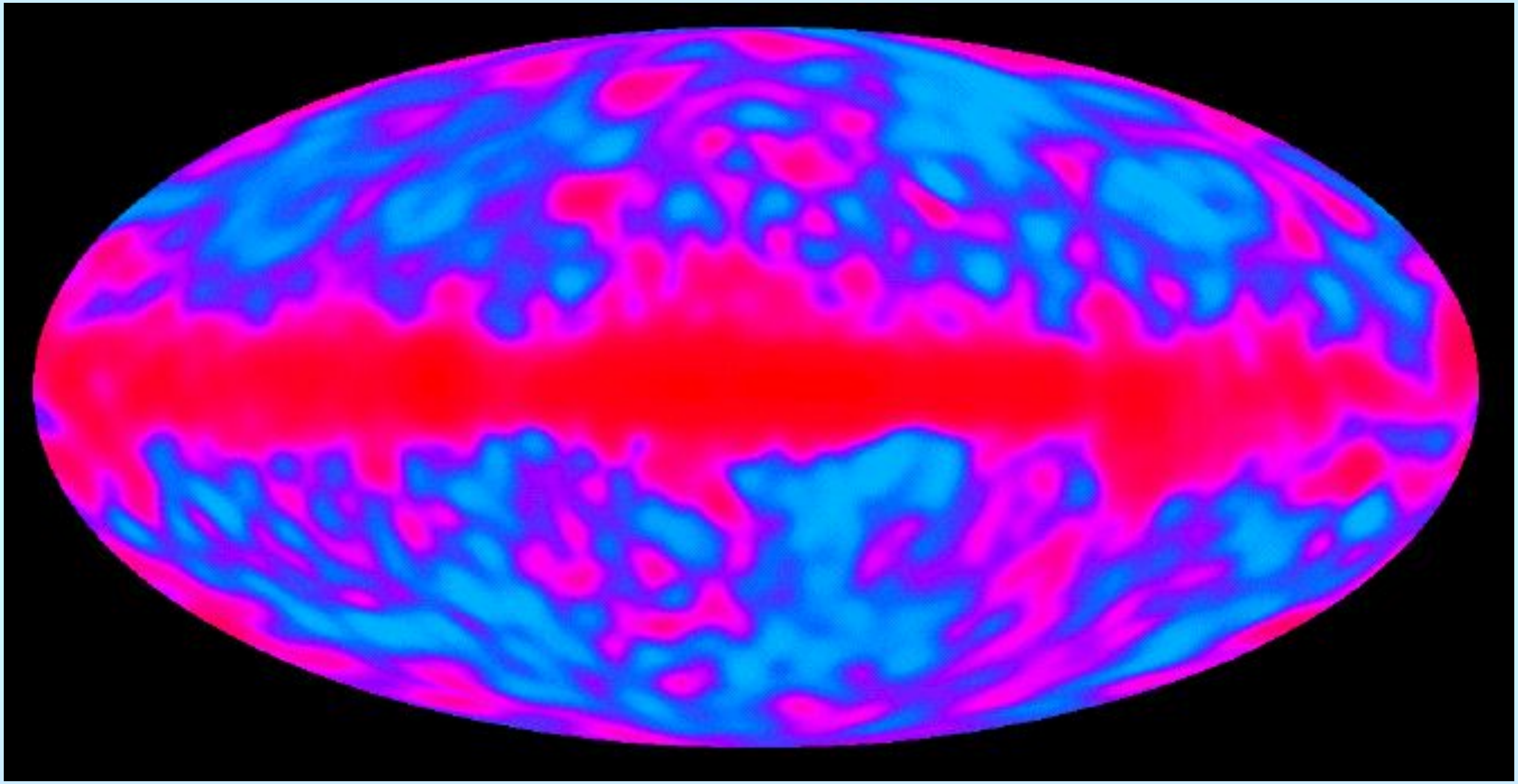
Because the Earth is moving through space, the microwave background has a dipole moment. COBE observed this quite easily.



The direction of the Earth's motion is towards $\alpha(2000) = 11^h\ 09^m$, $\delta(2000) = -6^\circ\ 42'$

# The All-Sky Microwave Background

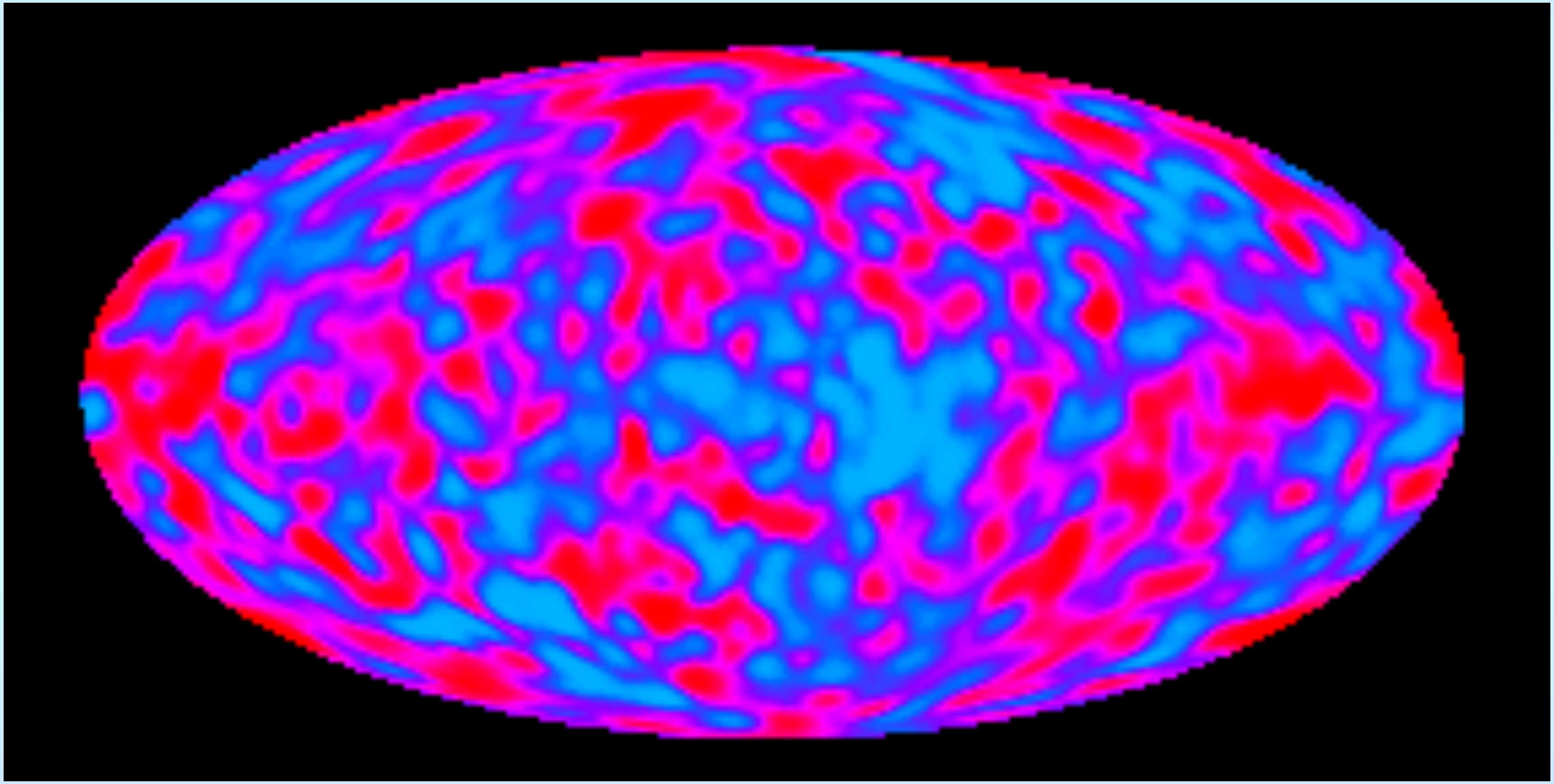
When the Earth's motion is removed, the distribution of microwaves on the sky becomes more uniform.



The plane of the Milky Way is easily visible.  This is due to thermal emission from cold dust and synchrotron emission from high energy electrons (produced by supernovae, etc.)

# The All-Sky Microwave Background

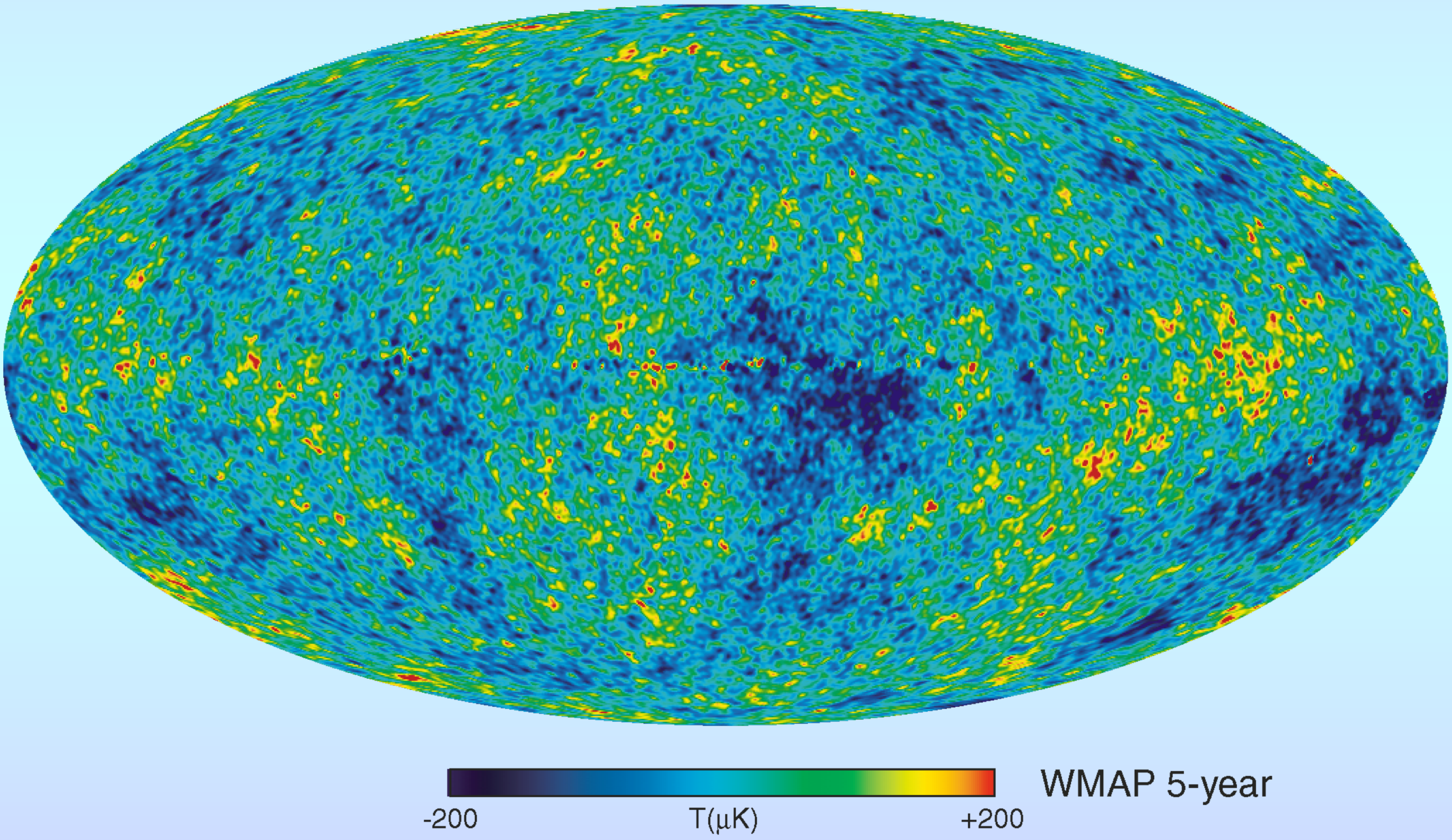
Finally, after removing the Milky Way's emission, we are left with the primordial fluctuations in the microwave background.



The fluctuations are only a few parts in 10,000

# The All-Sky Microwave Background

The spatial resolution of WMAP was much greater than that of COBE, allowing better measurements of $\delta T/T$ versus position.



The fluctuations in the microwave background can be quantified by turning the observed spatial distribution of hot and cold regions into a power spectrum.

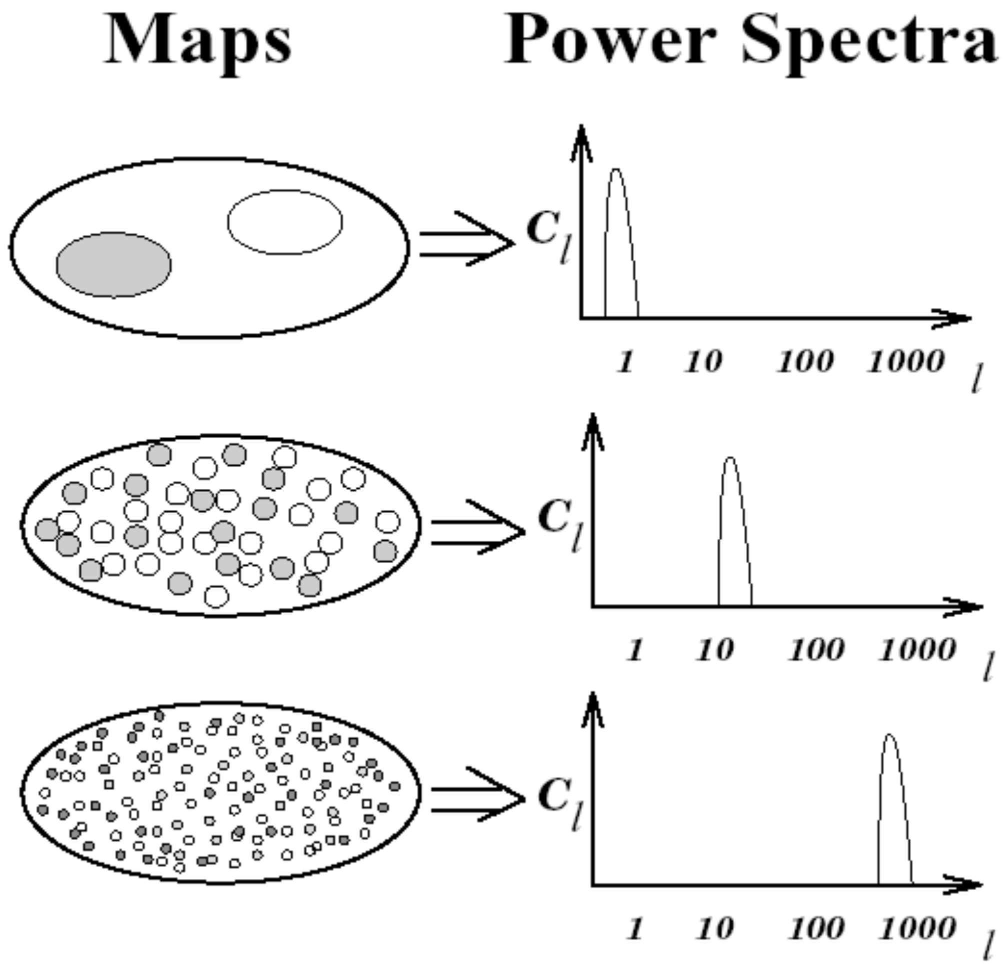



Figure 2. Simple Maps and their Power Spectra. If a full-sky CMB map has only a dipole (top), it's power spectrum is a delta function at $\ell = 1$ . If a map has only temperature fluctuations on an angular scale of $\sim 7^\circ$ (middle) then all of the power is at $\ell \sim 10$. If all the hot and cold spots are even smaller (bottom) then the power is at high $\ell$.

Simplified Power Spectra

# Cosmic Microwave Power Spectrum

The temperature fluctuations, $\Delta T$, are translated into the coefficients of spherical harmonics (note $\theta = 2\pi/l$)

$$\Delta T(\theta,\phi) = \sum a_{l,m} Y_{l,m}(\theta,\phi)$$

The power spectrum is then the sum of the squares of the coefficients

$$C_l = \frac{1}{2l+1} \sum_m a_{l,m}^2$$

(with the normalization)

$$\Delta_T^2 = \frac{l(l+1)}{2\pi} C_l T^2$$

# Cosmological Parameters

The amplitude and location of the acoustic peak depends on combination of

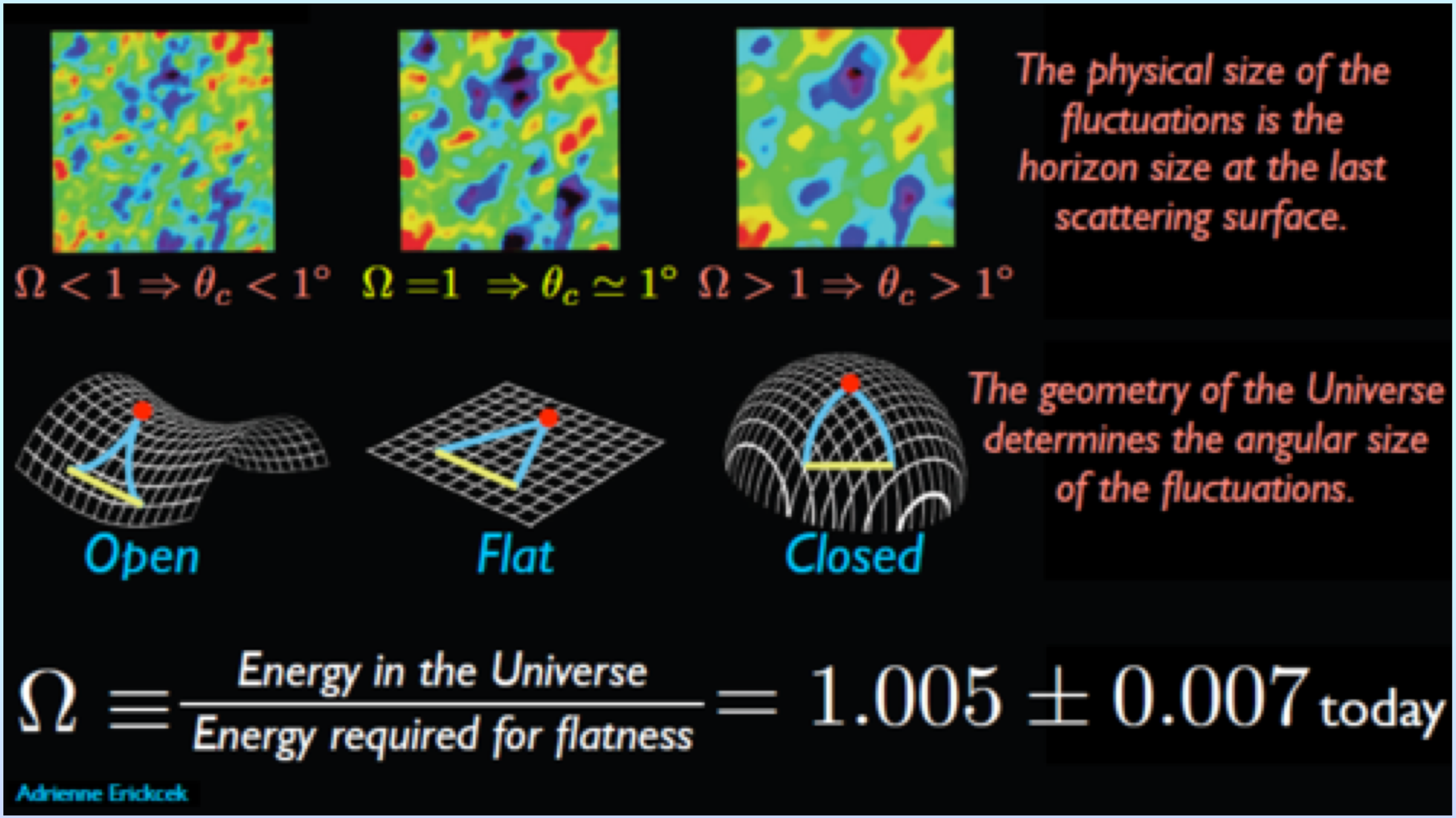
- The expansion rate of the universe
- The fraction of cold dark matter in the universe
- The fraction of baryons in the universe
- The fraction of hot neutrinos in the universe
- The epoch when the energy and matter densities were equal
- The amplitude of the initial fluctuations

The amplitude and location of where we *observe* the acoustic peak to be depends on

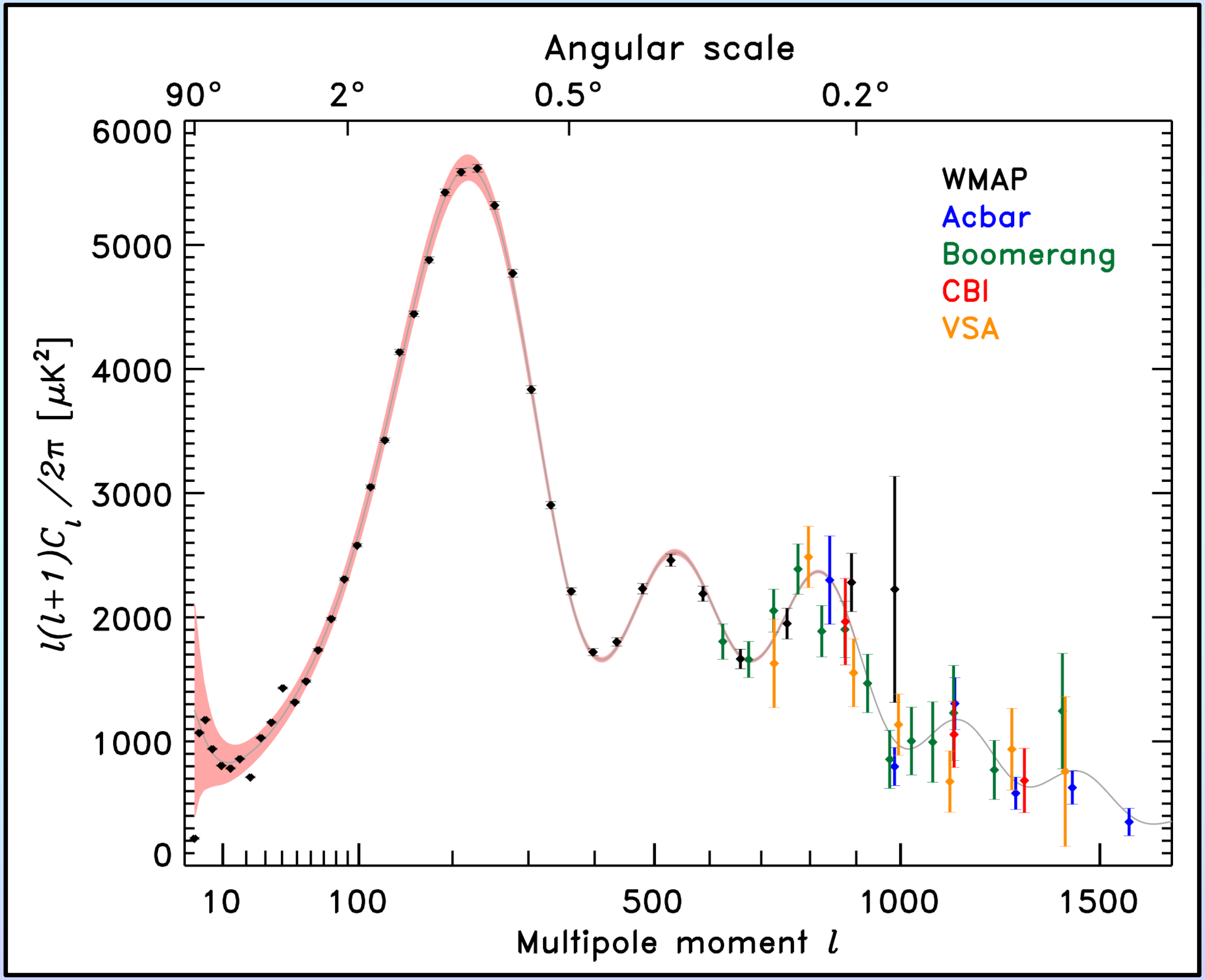
- The curvature of the universe
- The amount of dark energy in the universe
- The epoch of re-ionization

# Geometry Measurements

Our measurement of the angular position of the acoustic peak depends on the shape of the universe.



# The Observed CMB Power Spectrum



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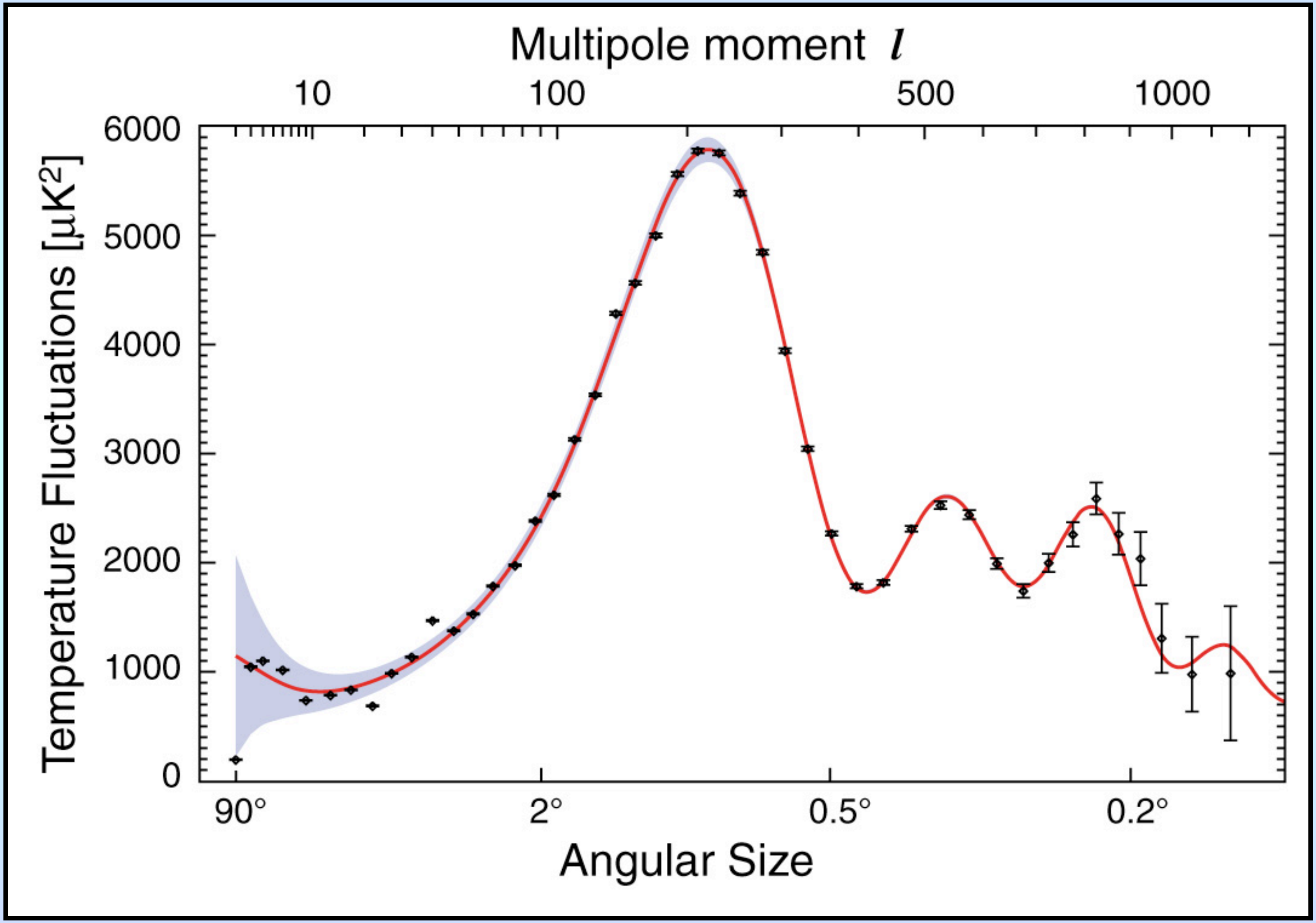

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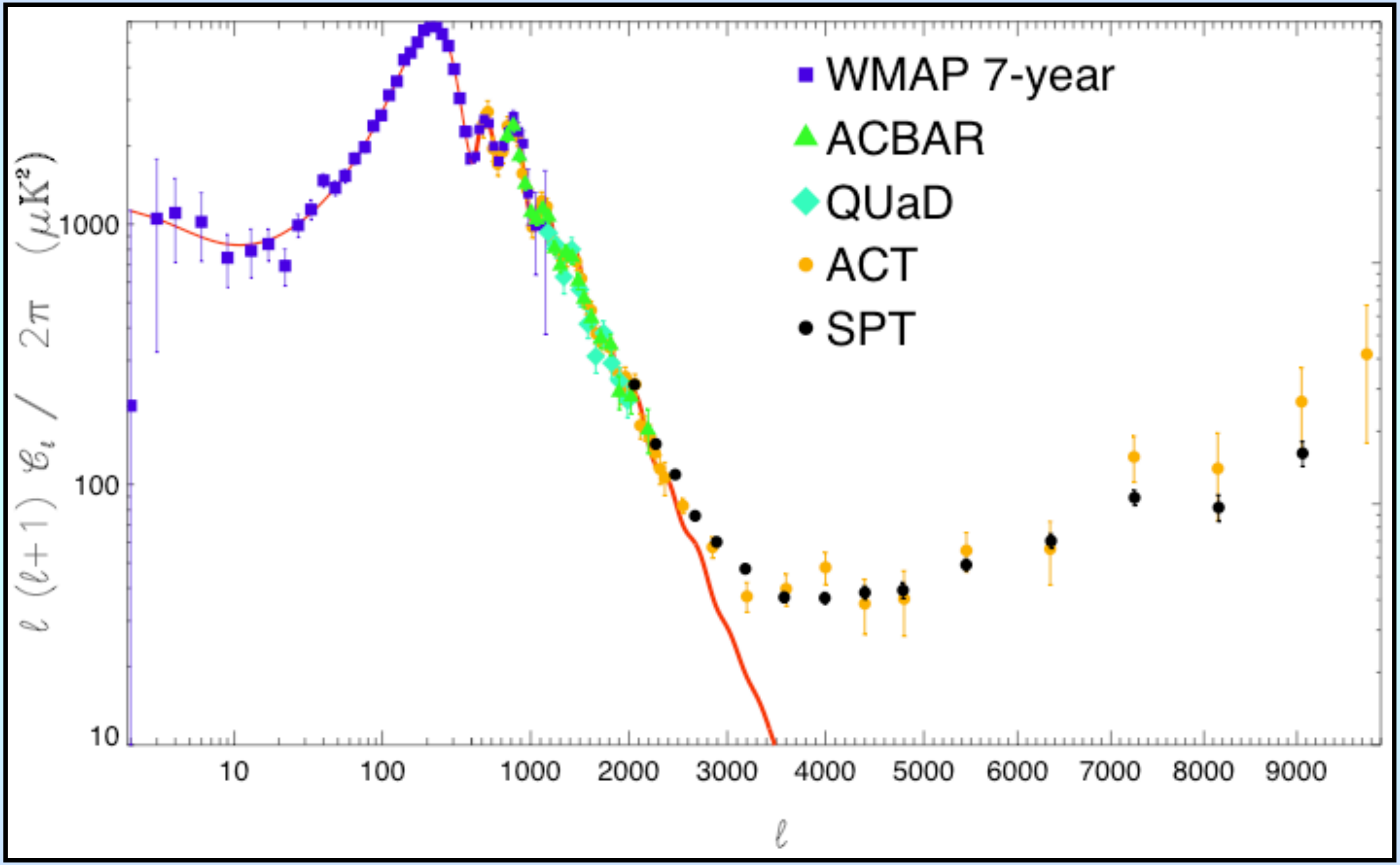
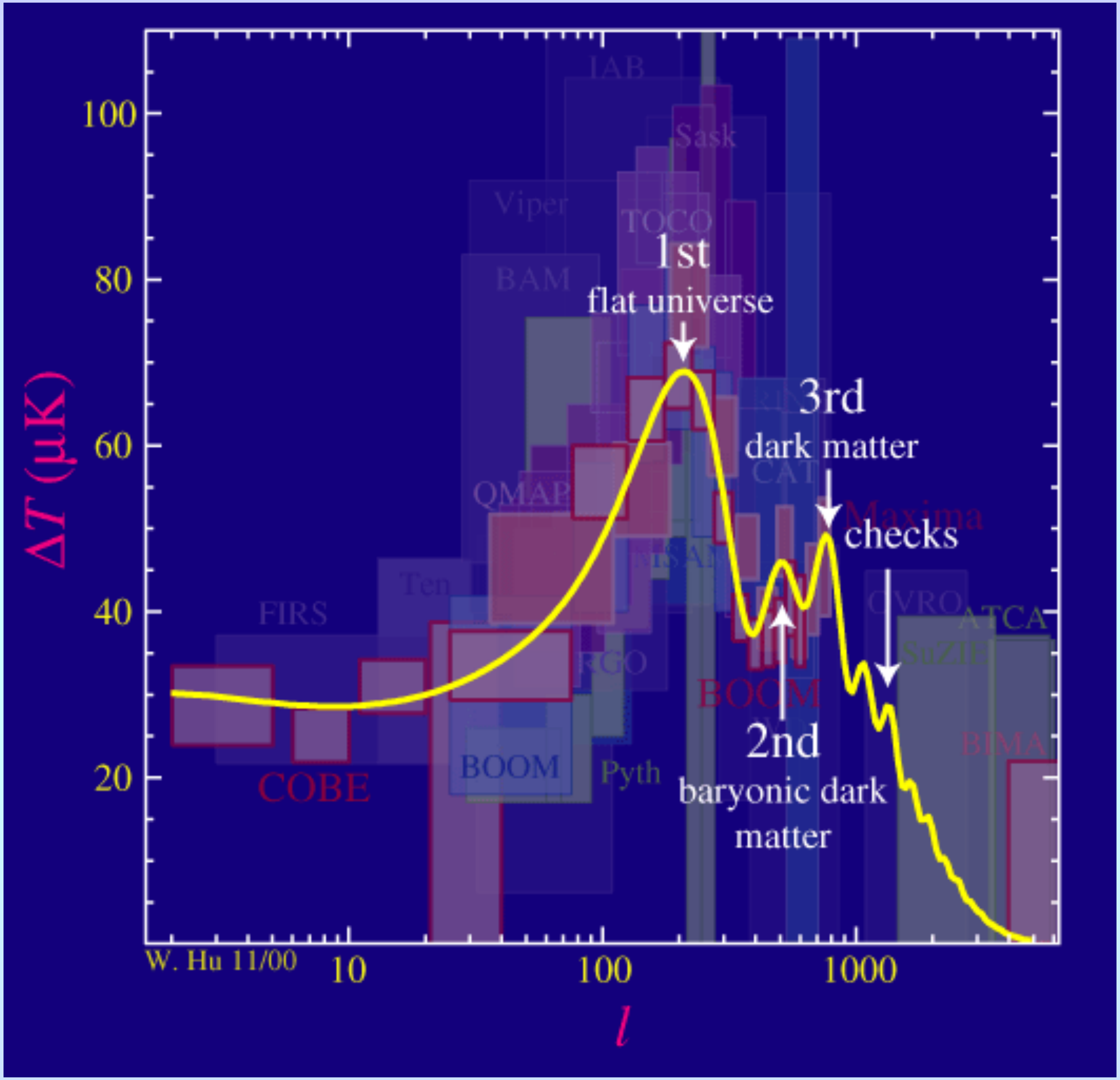
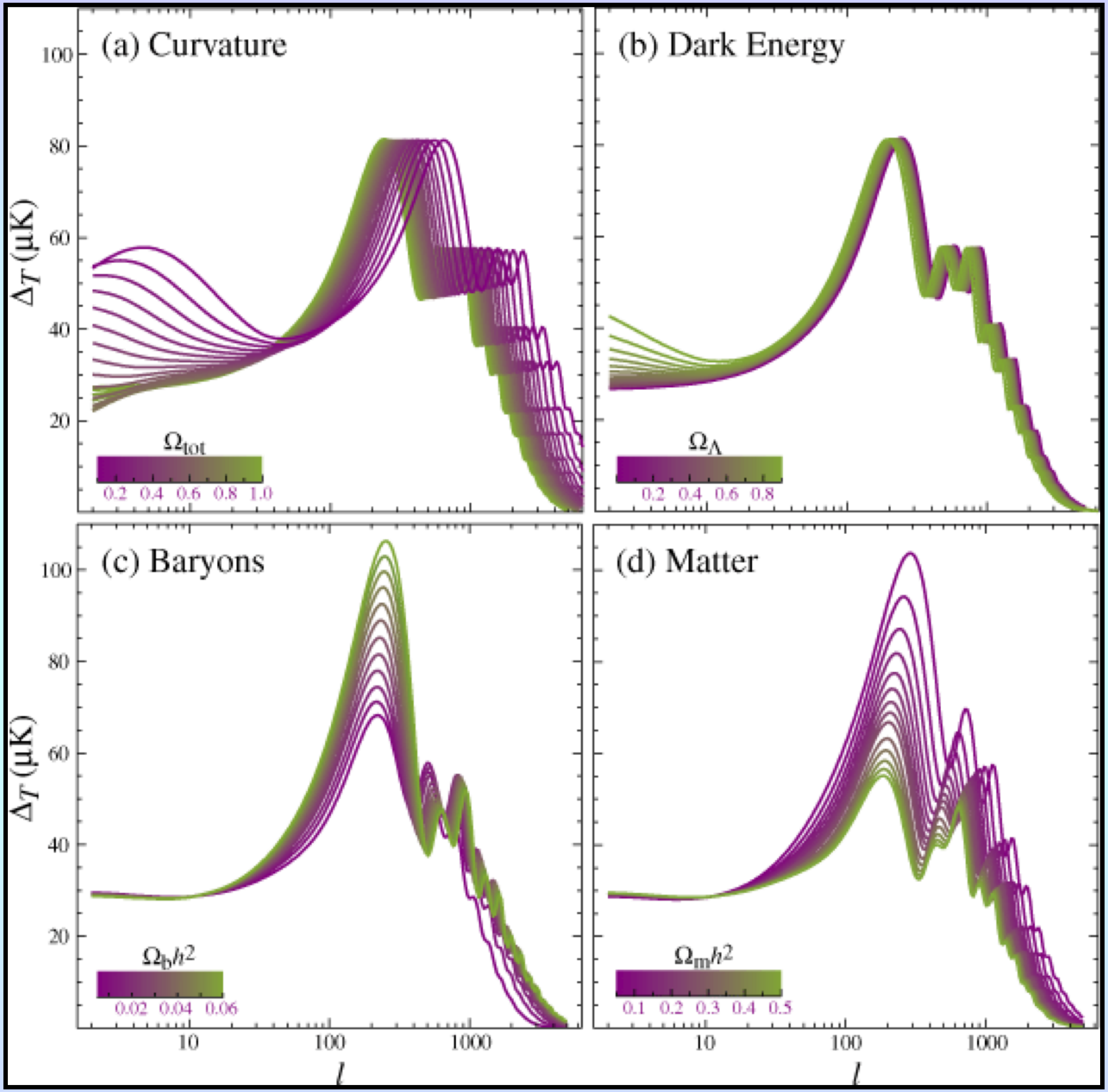





Angular power spectrum, courtesy of Wayne Hu




Parameter Dependence of Power spectrum -- Hu & Dodelson (2002)

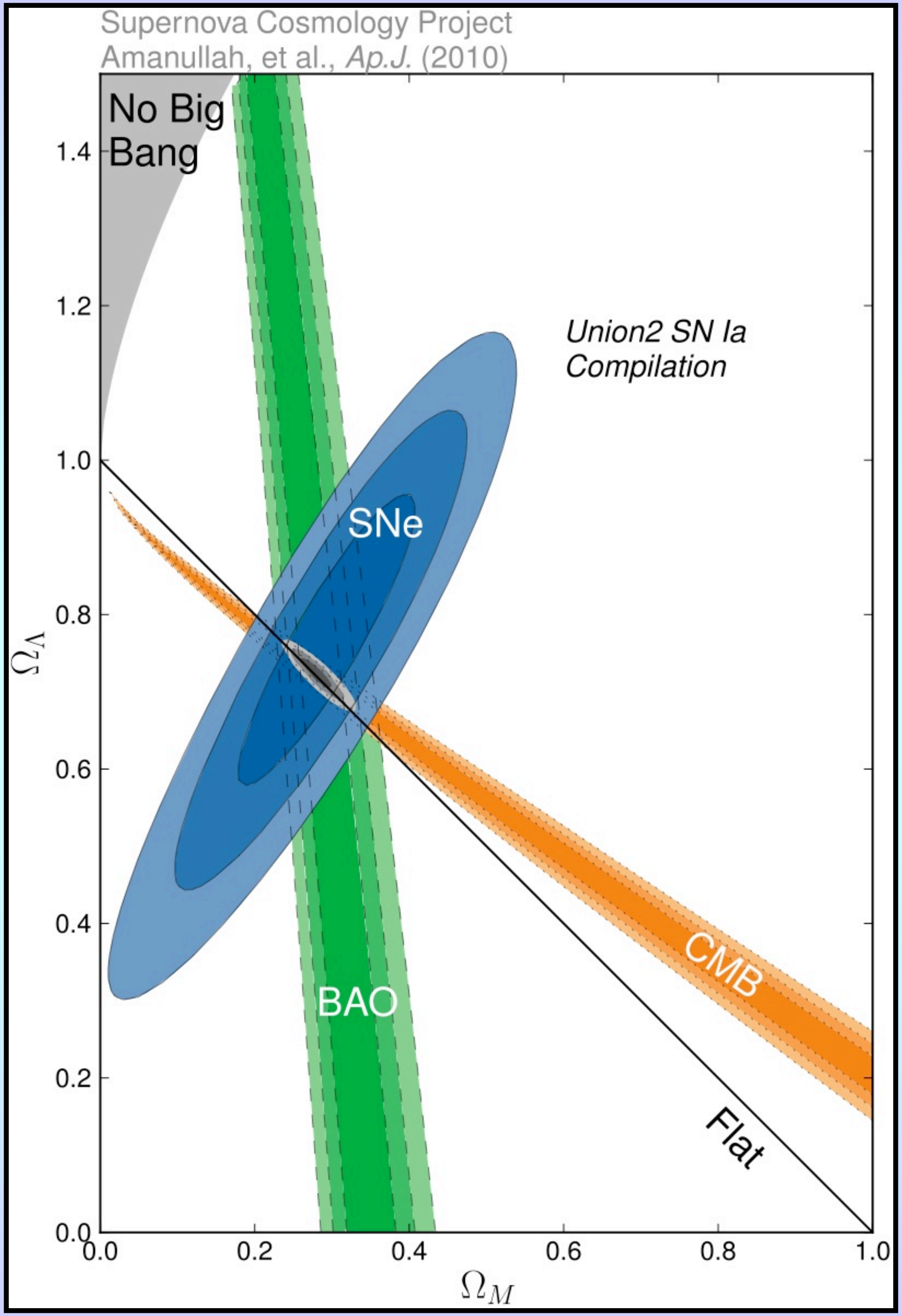
# Cosmic Microwave Background

WMAP and Planck have strongly confirmed the ΛCDM model implied by the Type Ia supernovae results!! Presently, the best-fit parameters (assuming a Cosmological Constant with $k = 0$) are:

- $\Omega_\Lambda = 0.6911 \pm 0.0062$
- $H_0 = 67.74 \pm 0.46$ km/s/Mpc
- $\Omega_{matter} = 0.3089 \pm 0.0062$
- $\Omega_{baryon} = 0.0486 \pm 0.0010$
- $\Omega_{dark} = 0.2589 \pm 0.0057$
- $\Omega_\nu < 0.003$ (95% CL)
- Age of the universe is $13.799 \pm 0.021$ Gyr

If the requirement of flatness is released, then

- $\Omega_{tot} = 1.0023 \pm 0.0055$
- $w = -0.98 \pm 0.053$




The best constraints on cosmological parameters come from a combination of data, including supernovae, the CMB, the large scale structure of galaxies, and the growth of galaxy clusters.